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AN INVESTIGATION OF THE PROBLEMS OF COST DETERMINATION FOR THE DISCOVERY, DEVELOPMENT, AND PRODUCTION OF LIQUID HYDROCARBON AND NATURAL GAS RESOURCES

John E. Hodges and Henry B. Steele

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By
John E. Hodges
Associate Professor of Economics at the Rice Institute
AND
Henry B. Steele
Assistant Professor of Economics at the Rice Institute

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PREFACE

THIS monograph is addressed to a problem of both practical and academic interest. Those in industry and government who are concerned with the formation of policies and operating decisions pertaining to energy resources are well aware of the practical need for and the difficulty of obtaining reliable cost data for the petroleum industry. As an academic problem, the determination of the cost of discovery, development, and production of liquid hydrocarbons and natural gas poses conceptual difficulties which are almost unique.

The discussion to follow contains no final solutions to the many problems of cost determination that confront petroleum industry accountants, economists, and managers. An attempt is made only to clarify some basic cost concepts, and to suggest simplified procedures which may allow more meaningful cost data to be developed.

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John E. Hodges
Henry B. Steele

Houston, Texas
August 1, 1959

AN INVESTIGATION OF THE PROBLEMS OF COST DETERMINATION FOR THE DISCOVERY, DEVELOPMENT, AND PRODUCTION OF LIQUID HYDROCARBON AND NATURAL GAS RESOURCES

INTRODUCTION

THE present investigation is concerned with the problems of determining the costs incurred in finding, developing, and producing liquid hydrocarbons and natural gas.

It is necessary at the outset to define the three categories of cost which will be adopted here, particularly since the definitions are not identical with those used by many students of the problem. The definitions are based primarily upon theoretical considerations, with the three categories being (1) finding cost, (2) development cost, and (3) production cost.

The first cost category is that of finding cost, or exploratory cost. (These two terms are used interchangeably.) This is defined to include all costs of lease acquisition, all geological and geophysical expenditures, the drilling costs of all exploratory wells, and the costs of completing the successful exploratory wells, through the installation of the Christmas tree.

The second cost category is development cost. This category includes the costs of all items which are necessary to develop the potential of an oil pool which has already been discovered. These include outlays to equip the successful discovery well for production following the installation of the Christmas tree, and outlays for the drilling of subsequent development wells to define the limits of the pool. Accordingly, development cost would include outlays on flow lines, separators, and storage tanks for the original discovery well, and all drilling and field-development outlays for all subsequent development wells, whether productive or dry.

The third cost category is production cost. This category includes current operating outlays that are made to secure production from existing wells. Major subclassifications would be (1) pumping or other lifting costs, (2) field maintenance and upkeep items, such as the current operating expenses of secondary recovery efforts (the capital expenditures for which would be included under development cost), and (3) continuing expenditures in connection with leasing or other land-use arrangements.

The ideal way to measure cost in the petroleum industry would be to compute the finding cost per barrel, the development cost per barrel, and the production cost per barrel, by comparing the relevant cost aggregates to the actual physical volume of fluid hydrocarbons found, developed, and produced over the life of the pool. Unfortunately, it is not a simple matter of selecting total dollar costs for finding, developing, and producing crude oil and dividing these data by the appropriate volumes. It may not be premature, at this stage, to list the major difficulties which are encountered in attempting such computations.

1. Lack of adequate information as to the volume of reserves added by a particular operation.
2. Lack of adequate information as to costs incurred for discovery and developmental effort.
3. Conceptual difficulties encountered in attempting to match the costs of a given year with the discoveries which may ultimately be attributable to the efforts of that year.
4. The perennial problem of the allocation of costs to the

jointly discovered products of oil and gas, a problem inescapably arbitrary in its manner of resolution.

This introduction has presented the problem, set forth the definitions of the cost categories to be employed in the analysis, and indicated where major difficulties will be encountered. The discussion itself will be organized in three sections. In the first section, several of the more ambitious recent attempts to determine costs for the petroleum industry will be reviewed. It will be shown that these studies have not been uniform in their approach and have dealt in different ways with different aspects of the problem.

The second section consists of an analysis of the problems which would be encountered in a comprehensive study, together with suggestions regarding methods for making such a study where the researcher must rely chiefly on currently available data.

The third section of this paper attempts to measure and to assess the significance of trends in the costs of crude oil exploration, development, and production. It is recognized that the data ideally required for such a project are not available at present; however, there are two compelling reasons for measuring cost trends with the data that are available. First, such a procedure makes the recommendations of Section II pertaining to future data collection far more concrete than they could possibly be in the absence of any empirical analysis. Second, the behavior of crude oil costs is of such obvious significance to the industry and to the public that even partial and incomplete findings are valuable. It must be emphasized, however, that Section III is in the nature of a progress report. Further progress awaits improvement in the quality of the basic data upon which serious cost studies must inescapably rest.

I. A SURVEY OF RECENT COST STUDIES

THE great majority of the articles which deal with the cost of finding, developing, and producing oil and natural gas are partial in coverage, or largely speculative in nature. We shall single out for consideration only those articles which are (1) reasonably recent, (2) comprehensive in scope, and (3) relatively explicit as to sources and methodology. This limits the field to a very few studies of particular interest and value. Even so, these pioneering studies are often lamentably reticent as to their sources and methods of analysis.

The first studies to be considered are the investigations of exploration costs which have been published by H. J. Struth for a number of years.[1] Struth's chief contributions to the literature of discovery costs and yields are contained in two sets of estimates. The first of these deals with what he terms "exploration costs,"[2] and the second presents the results of his efforts to allocate subsequent extensions and revisions to an oil field or pool back to the year of initial discovery. We shall consider each contribution in turn.

Struth is interested almost exclusively in what corresponds to our first cost category, that of finding costs. He is interested in computing the per-barrel finding cost for the oil discovered in a given year, and in revising this cost in the light of additional information concerning the magnitude of these discoveries revealed in subsequent years. But we must distinguish Struth's definition of finding costs from that which we prefer to employ in the present treatment. We define finding costs to consist of all expenses which lead to, and are expended in, the drilling of exploratory wells.

One useful and comprehensive definition of an exploratory well is that employed by F. H. Lahee, and presented in annual statistics published in the *Bulletin of The American Association of Petroleum Geologists.*[3] All wells drilled are classified as (1) field-development wells, or as (2) exploratory wells. Field-development wells are those which are drilled over proved structures. Exploratory wells consist of (1) new-field ("rank") wildcats, defined as wells drilled on structures that have never produced, or, where structures are geologically indefinite, wells located more than one-half mile from the nearest producing well; and (2) new-pool or extension ("outpost") wildcats, defined as wells drilled on structures already producing but anywhere from one-half mile from the nearest producing well (where formations are very indefinite) to two miles from the nearest producing well (where formations are more clearly demarcated). All exploratory wells must therefore be at least one-half mile from the nearest producer; any wells which are closer are classified as developmental wells. The chief virtue of making a distinction between exploratory and developmental wells lies in the division between a relatively low-risk and a relatively high-risk operation. For an exploratory well, there is a higher probability of a dry hole, but there is also a higher probability of obtaining a larger increment to total discoveries than is the case with a developmental well.

There is nothing inherently logical about the one-half-mile distinction between exploratory and developmental wells, but its employment by Dr. Lahee in his annual statistical reports gives it some weight of authority which would seem to justify its use. Struth, however, defines "exploration costs" to include the cost of exploratory wells as the term is used by Lahee, and also the cost of dry developmental wells. This seems unnecessarily arbitrary. If, for instance, the best available geological and geophysical information gives two developmental wells equal chances of finding oil under a suspected portion of a given pool, then one is neither more nor less "exploratory" than the other, despite the fact that one finds oil and the other does not. On the contrary, both are less "exploratory" than a new field or new pool wildcat, if by exploratory one implies the presence of a certain degree of risk of failure. Struth's method is a compromise which overestimates exploratory effort in terms of the amount of drilling done at the typical exploratory risk (about 8 to 1, for the years he considers). Furthermore, his method gives a downward bias to the average discoveries per "exploratory" well, including as it does only those developmental wells which made no addition to cumulative total discoveries. Equal numbers of "exploratory" wells in two consecutive years would not be comparable if the ratio of developmental dry holes to genuine exploratory wells differed; an increasing ratio of developmental dry holes to total exploratory wells would obscure the trend in the results of exploratory effort properly defined.

Struth makes the following breakdown of his "exploratory costs" for the years 1936-1953:

1. Drilling costs
2. Cost of leasing
3. Geological and geophysical costs
4. Overhead and other costs

These four categories are nowhere defined item by item, nor is there to be found any explanation of the sources of the data, the methods of collection and processing, or the probable margin of error associated with the statistics. It is to be presumed that the data were derived from surveys; but without any information as to the size or composition of the survey sample, it is impossible to evaluate the significance of Struth's findings. This is perhaps the reason why his data have been used infrequently by students of the cost problem, even though there is apparently no comprehensive alternative series of costs available.

With regard to Struth's second contribution, that of the adjustment of extensions and revisions of reserve estimates back to the year of the original discovery of the field or pool, the same observations apply. Struth is apparently the only one to attempt such a calculation. This is a task of considerable magnitude, concerning which many questions arise as to sources of information, methods of adjustment, and the associated margins of error. Furthermore, there is considerable doubt as to the meaning of the results, apart from questions of statistical accuracy. The significance of a readjusted total of gross reserves discovered cannot in all instances be compared with the gross costs incurred in the original year of discovery, unless the subsequent extensions and revisions have been realized without the necessity of incurring additional costs in subsequent years, which is quite unlikely. (These problems are discussed in the second section of this paper.)

* * *

The second study to be considered is that published by P. R. Schultz in 1953.[4] The emphasis of this study makes an interesting contrast with that of Struth. Struth is interested in the measurement of finding costs, and in obtaining essentially a single measure for this purpose: the dollars-per-barrel cost of finding oil, as adjusted in the light of subsequent information concerning the discoveries in the original year. Schultz is also interested in finding costs but he regards the problem as too complex to be dealt with successfully by any single statistical series. Instead of employing dollar-volume estimates of finding costs, he studies several dimensions of "real" cost measured in terms of exploratory effort using the exploratory well as the ideal unit. His study of finding costs, as conceived in these terms, is notable for two analytical features: the employment of the volume of discoveries per dry hole as an estimate of the rate of discovery,[5] and the expedient of measuring the volume of discoveries per dry hole relative to total cumulative discoveries, as well as measuring it relative to the year-by-year time trend. Such a procedure is surely appropriate. The rate of discovery at any point in time is obviously to some extent a function of the rate of discoveries in the past, since oil deposits are ultimately fixed in supply and the greater the rate of discovery in the past, the smaller will be the remaining universe of potential discoveries. Other things (such as the rate of exploratory effort) being equal, the subsequent rate of discovery will be lower. Hence the rate of discovery is related primarily to cumulative discoveries, and only indirectly to calendar time.

Schultz's reliance upon current year net discoveries (in barrels of crude oil and natural gas liquids) per dry hole is of course an example of the use of an index of average productivity from which to infer the behavior of discovery costs. Let us inquire into the reasons why Schultz chooses this particular measure. It is apparent that it is simply due to the limitations of available data. Schultz would like to compute the number of barrels of crude oil and natural gas liquids discovered per exploratory well (using wildcat wells only), with extensions and revisions credited back to the year of original discovery. However, he feels that it is impossible to attempt this backward revision because of the difficulty of making the compilations for remote years, and because of the underestimation of the results of recent-year exploration simply because insufficient time has elapsed to give a complete picture of subsequent-year extensions and revisions. These problems must be regarded as formidable ones. It would be difficult, although not impossible, to assign known extensions and revisions to individual fields and to the years of original discovery; but it is impossible to adjust recent years' initial discoveries for ultimate extensions and revisions because these are not known.

Similarly, Schultz finds it necessary to employ total dry holes as an estimate of total exploratory wells. This is because reliable statistical reporting on the number of exploratory wells (according to the definition given above) dates only from 1937. Data on the total number of dry holes, however, goes back to around 1900. It might seem paradoxical to measure the success of exploratory drilling in terms of the total number of wells which were not successful. Obviously, if exploratory wells are significantly riskier than developmental wells, then the more exploratory wells there are, the more dry holes there will be. However, this overlooks the fact that the relative success ratios of exploratory and developmental wells are not identical. To be precise, dry holes will constitute a reasonably consistent estimate of total exploratory wells only under certain very special conditions. Let

W = total number of wells completed in the year
ϕ = per cent of total wells that are exploratory in nature
θ = per cent of total wells that are developmental in nature (assuming that $\phi + \theta = 100\%$)
α = success rate (in per cent) for exploratory wells
β = success rate (in per cent) for developmental wells
W_o = total dry holes drilled in the year;

then $W = W(\phi + \theta) = \phi W + \theta W$

$$W_o = \phi W\,(1 - \alpha) + \theta W\,(1 - \beta)$$

and: $$\frac{\phi W}{W_o} = \frac{\phi W}{\phi W(1 - \alpha) + \theta W(1 - \beta)} = \frac{\phi}{\phi(1 - \alpha) + \theta(1 - \beta)};$$

hence: $\frac{\phi W}{W_o}$ is constant when ϕ, θ, α, and β are all constant;

$\frac{\phi W}{W_o}$ decreases if, *ceteris paribus*, ϕ decreases; θ increases; α decreases; β decreases;

$\frac{\phi W}{W_o}$ increases if, *ceteris paribus*, ϕ increases; θ decreases; α increases; β increases.

Dry holes will be a consistently good estimate of total exploratory wells only when the ratio between the two is constant, or is very nearly constant. This means that $\frac{\phi W}{W_o}$ must be constant, but this can occur only when the success rate of exploratory drilling, the success rate of developmental drilling, and the ratio of exploratory to developmental wells are all constant. (A possible exception would be any of the highly unlikely instances where ϕ, θ, α, and β might display mutually compensating variations.) In recent years, the only one of these variables to remain roughly constant has been the success rate of exploratory wells. Before 1957, the ratio of exploratory to developmental wells had been increasing, which would have tended to make the use of dry holes overestimate total exploratory activity. In recent years there has been some decrease in the success rate of developmental wells, which would correspondingly tend to make the use of dry holes underestimate total exploratory activity. In general, dry holes will be only a rough measure of total exploratory activity.

Schultz maintains that there is a certain offsetting of biases which occurs in the utilization of two approximate measures, dry holes and unadjusted current year net discoveries.[6] His reasoning may be reconstructed as follows: If we plot dry holes against historically-adjusted reserve discoveries, we are guilty of attributing the end results of exploratory drilling (i.e., the subsequently-adjusted-reserves totals) to the total of both exploratory and developmental drilling. This is conceptually inaccurate, and bias will be introduced to the extent that changes occur in the ratio of exploratory wells to developmental wells. Schultz then contends that if we are forced to use current year net discoveries, the number of dry holes then becomes a more appropriate factor for comparison. Current year discoveries consist of new discoveries, extensions, and revisions. Since "each and every well drilled is an endeavor to find oil," the dry development wells are therefore a measure of the effort to extend fields, while the exploratory dry holes are a measure of the effort to find new fields. Thus the total of all dry holes drilled, developmental plus exploratory, is an acceptable index of the effort expended in making unadjusted-current-year additions to reserves.[7]

It would seem necessary to enter two objections at this point. First, it is likely that there is a bias of a somewhat subtle nature present in the mere use of unadjusted-current-year reserve additions. It is widely recognized that the bulk of our crude oil reserves is to be found in a relatively small number of "giant" fields.[8] These fields introduce large initial-year discoveries and large extensions and revisions into the record of cumulative discoveries in ways which are to some extent independent of discovery efforts in particular years.

However, it is not possible to state with certainty that this is the case, although available information seems to confirm such a view. Actually, the data are so unsatisfactory that one would be hard pressed to refute the opposite contention that for a large field, initial-year reserve estimates are likely to be unusually high, and subsequent extensions and revisions therefore low. The prudent course is to content ourselves with the observation that, in either case, bias would result if the size-distribution of fields were not identical in all years. A year marked by the discovery of an unusual number of "giant" fields would bias the subsequent years either upward or downward, in the sense that not only the magnitude of discoveries, but also the ratios of new discoveries to extensions and revisions would be governed both by current-year effort in drilling, and by drilling results in the recent and intermediate past. (Even if all fields, regardless of size, grew at the same rate through extensions and revisions, it would still be next to impossible to conceive of a situation where bias of some sort could not appear.)

As a second point of criticism, it may be asked why Schultz does not simply resort to the use of *all* wells drilled during the year, exploratory and developmental, as an index of the real cost of discovery. If "each and every well drilled is an endeavor to find oil" then it would perhaps be better to use the total number of wells drilled to measure the real cost of discovery.

Schultz undertakes one further adjustment of the basic data. He computes three-year moving averages of the series on discoveries per dry hole, and plots the adjusted data against time in years, and cumulative discoveries in billions of barrels. The moving averages are apparently used in order to reduce the element of purely random variation which seems to be quite large. During 1930-1933 the data show evidence of extreme variations which must be attributed to other factors than the productivity of petroleum technology. There is, however, no indication of a three-year cycle in drilling activity, or in the dry-hole ratio. Schultz examines the dry-hole ratio since 1860, and finds that these data seem to be characterized by secular trends with no appreciable cyclical component. There is, for instance, a marked decreasing trend from 1870 to 1880, a more or less stationary trend from 1890 to 1914, and a sharp upward trend since 1938.[9] Therefore, there is no likelihood that the smoothing was intended to eliminate a cycle in drilling, as evidenced by the dry-hole ratio. On the other hand, Schultz contends that averaging the three-year periods takes into account some part of subsequent extensions and revisions. This is no doubt true; it is unfortunate that one is unable to determine how large a part of total ultimate extensions and revisions will have been registered in the first two years following discovery. On the whole, however, this seems to be a rather short interval since reserve estimates for important fields have been revised and revised again over periods as long as thirty years.

It should be noted that Schultz finds that the discovery rate, measured in barrels of crude oil and natural gas liquids discovered per dry hole, reached its peak in 1938 and has declined since that time, the decline after 1947 being steady (keeping in mind that three-year moving averages are employed). In order to show that this trend holds for the United States as a whole and also for each of the major oil-producing states, the author calculates the same data for Texas, California, Louisiana, Kansas, and Oklahoma. The results substantiate his claim: Texas, California, and Louisiana all reached their peaks in 1938, Kansas in 1936, and Oklahoma in 1937. In all states, except Louisiana with recent offshore discoveries, the discovery rate has declined slowly but steadily from the late thirties.[10] It must be noted, however, that data on a state-by-state basis seemingly were not collected prior to 1935.

Schultz introduces one final comparison which is of interest. In an attempt to find a single index of "reserve-developing power," he uses the number of barrels of crude oil and natural gas liquids discovered on a current year basis, excluding all revisions of previous year estimates (but not excluding extensions), and divides this magnitude by the total number of wells drilled during the year. The data are interpreted as showing the number of barrels of reserves added per well drilled.[11] The result is a moderate upward trend between 1945 and 1951 (also on a three-year moving average basis). This is an interesting calculation. If revisions are indeed the dominant factor in distorting the relationship between current drilling and current additions to reserves, a significant conclusion can be drawn. Since revisions are almost never downward, ignoring this component of total discoveries will practically never overstate reserves added per well. An increasing trend would mean that, apart from any legacy from past giant fields, the oil exploration phase of the industry would be better than holding its own on a per-well basis.

However, it is to be expected that extensions also depend a great deal on the pattern of discoveries in the past. New discoveries and extensions cannot really be treated as if they were homogenous unless the risk involved in undertaking the search for each happens to be identical. Rather than comparing new discoveries plus extensions with exploratory wells plus developmental wells, it would be more instructive to compare new discoveries with exploratory wells (for the available time period) and extensions with developmental wells, each calculation being made separately.

• • •

The third study to be considered is the most comprehensive and the most advanced in its methodology.[12] It is also the most ambitious. Warren Davis sets out to discover the chief determinants of the ultimate oil production in the United States, and to estimate ultimate recovery under a variety of assumptions as to the probable effect of these determinants as variables. In doing so, he presents a method of predicting the future petroleum productive capacity of the United States, and gives examples to illustrate how wide a range of variation in productive capacity might be expected under different technological and economic conditions.

Basic to Davis's approach is the assumption that for the foreseeable future (a 45-year extrapolation is made), production will be governed by limitations in supply rather than by changes in demand. Demand is assumed to be increasingly in excess of future productive capacity. Davis bases this assumption primarily upon the evidence of decreasing returns to total drilling activity.

Other problems to which Davis addresses himself are of broader scope than the task of cost determination, which is the major concern of this study. We shall not limit ourselves, however, to the discussion of this single aspect of Davis's study, but will consider the significance of the contribution made by his paper as a whole. This is done for two reasons: (1) Davis illustrates the manner in which an index of real drilling costs, stated as a national average, can be employed as a crucial part of a comprehensive system of forecasting for the petroleum industry, and (2) the manner of application of this real cost index is in itself interesting, demonstrating in a compelling fashion the dependence of an elaborate forecasting system on a single crucial variable, and thereby pointing up the need for obtaining an accurate body of cost data for the industry.

Davis does not investigate any of the three categories of finding, development, and production costs. Rather, he makes use of one index of real finding costs, namely the number of barrels of oil discovered per foot drilled; and he estimates other components of total dollar cost to supplement this approximation to finding cost. Let us consider the manner in which Davis carries out these computations.

Davis concedes that the ideal way to measure drilling returns would be in terms of actual finding and development cost per barrel, but considers accurate data of this type too difficult to secure.[13] He prefers to use as a substitute measure the gross ratio of increments to total cumulative discoveries (new discoveries, extensions, and revisions) to the total footage drilled (exploratory and development footage combined). Davis then plots this ratio for the period 1936-56 against cumulative total discoveries, the same magnitude used by Schultz. (Davis refers to this magnitude as "cumulative reserves developed.") He extrapolates this trend into the future, giving three alternative exponential extrapolations. The first is an extrapolation based on the fit for the period 1936-56, which has a pronounced downward slope. Davis refers to this as the "best" expected return. He then extrapolates on the basis of the fit for 1948-56 where the downward slope is more accentuated. This is referred to as the "worst" expected return. Then a third extrapolation is made by determining the midpoint between the "best" and "worst" predictions and referring to it as the "average" expected return.

In explaining these calculations, no mention is made by Davis as to the reasons for choosing the particular years used for the extrapolations. The gross ratio of cumulative discoveries per foot drilled could be carried back to 1925 quite readily, and to about 1918 with some loss of accuracy, but no significant loss of comparability. Only if the measure had been more limited as to the type of reserves discovered (for example, new discoveries plus extensions) would it have been necessary to begin with 1936. The difference it makes is obviously related to the character of the extrapolation. The decline in the ratio of cumulative total discoveries to footage drilled begins in 1937 and a decreasing extrapolation seems very much in order. If, however, the series had started in 1934, the marked increase between 1934 and 1937 would have suggested that another curve, perhaps of parabolic form, might be in order. Similarly, the selection of 1948-56 as the basis for the "worst" extrapolation is unexplained. No equations are given for the extrapolated predictions, nor are there any correlation coefficients or standard errors of estimate which might well have been included to facilitate evaluation of his findings.

Davis relates his many variables in the following way: the future pattern of discoveries and proved reserves depends upon the supply of and the demand for crude oil. (Davis works in terms of crude oil throughout, but takes natural gas into account when considering total revenue from drilling operations.) The demand is regarded as increasing at a constant rate and two assumptions are made as to this rate, namely 1½ and 3½ per cent per year. Supply is given the chief attention, as might be expected. Supply depends upon the drilling rate, which is related to total revenue from operations and to Gross National Product. Here, Davis does give the equation for the relationship:[14]

$$P_d = 0.80\ (P_r + P_g)$$

where: P_d is the percentage change in total footage drilled from the previous year.

P_r is the percentage change in crude oil revenue from the previous year.
P_g is the percentage change in Gross National Product from the previous year.

For this equation, an "average error" of about five per cent is reported. Davis compares annual drilling estimates computed from the equation with actual footages drilled for 1929-1941 and 1946-1956. The similarity is impressive. But all such relationships are notoriously unstable when used as the basis for extrapolation.

Davis does not relate supply directly to imports. Instead, he regards imports as being unlikely to increase rapidly enough to act as a greater check upon domestic production than the fact of decreasing returns to drilling, although he concedes that his import figures are very much subject to forecasting error. Of the two determinants, Gross National Product is apparently assumed to increase at some constant rate. Total revenue, on the other hand, depends upon a more complicated calculation involving the prices of crude oil and natural gas; the cost of exploration, development, and operation; and the physical returns to drilling.

The physical returns to drilling are derived from his extrapolations of crude oil discoveries per foot drilled, depending upon the choice of the "best," "average," or "worst" projections of the drilling return.

All cost elements are also related to the increase in cumulative total discoveries over time, with increases in costs occurring because of diminishing availability, and decreases occurring because of projected technological improvements. All cost factors are related to footage drilled, which is in turn related to barrels discovered. Footage drilled, however, is separately calculated as to exploratory and developmental drilling, and depth trends are computed for each type of well. The trend in the ratio of exploratory to developmental wells is also computed and projected, and on this basis, cost estimates are made. The procedure is as follows: Take the required domestic production for the year, as it results from the estimates of total demand and imports. This may be, for example, three billion barrels. Add this to cumulative discoveries as of the beginning of the year. Then divide the number of barrels of discoveries needed (three billion) by the appropriate extrapolated value of the drilling return ("best," "average," "worst") to obtain the number of feet to be drilled. Now it is necessary to relate footage drilled to total cost of exploration, production, and operation. (The illustration given by Davis refers to a "typical" developmental well, but it is apparently possible to extend the example to cover the general case of all wells drilled during the year.) Graphs have been plotted which relate the average depth of exploratory and developmental wells to total cumulative discoveries, and also relate the ratio between exploratory and developmental wells to total cumulative discoveries. Over the three billion barrel interval, averages presumably could be found for the depths of each of the two classes of wells, and for the ratio of exploratory wells to developmental wells. Given the total required footage, the number of exploratory and developmental wells could be computed. The total money cost of drilling and completing all wells can be obtained from the relationship between well depth and total cost in 1953, published in the Joint Association Survey dated April 12, 1956.[15] This cost is expected to decline over time, on a per-well basis. Davis projects a 1950-1955 trend[16] which shows that cost per well (measured in terms of 1955 dollars) may decline at the rate of approximately one per cent of the 1955 level for each two billion barrels of total cumulative discoveries of crude oil after 1955.

Other costs, however, remain to be included, and these cannot be expected to decline over time, at least not to the same extent as drilling costs. Davis adds 30 per cent to drilling costs to cover such items as fresh-water systems, salt-water-disposal systems, pressure-maintenance plants, etc. Exploratory costs other than drilling, i.e., geological and geophysical costs, are estimated at 200 per cent of drilling costs. Lifting costs are estimated at $275 per well-month, the production tax at 20 cents per barrel, and overhead at 18 cents per barrel. No sources are given for any of these estimates.

Why this emphasis on cost, if drilling can be determined by changes in total revenue and in Gross National Product alone? Davis observes that during the periods 1929-1941 and 1946-1956, it was not necessary to introduce profitability in order to explain the rate of drilling that took place, and concludes that in the past the profitability of drilling has not had much effect on the drilling rate.[17] But he points out that if the drilling return continues to decline, profitability will fall so low that it is bound to affect drilling. Davis believes that drilling has been limited chiefly in the past by the availability of capital, hence the importance of the total revenue variable. In the future, profitability may be the critical determinant. Consequently he devises a way of relating drilling effort to profitability.

In computing profits, Davis allows for percentage depletion and for the deduction of intangible drilling and development costs as a tax credit. On the assumption that a return of at least 10 per cent on invested capital is needed to compensate the investor for his risks, he determines a price per barrel for crude oil that would just be sufficient to yield 10 per cent on invested capital. This is done by implicitly ignoring the fact that oil and gas are joint products. A total dollar figure per barrel of crude oil is first arrived at, and then a trend projection of natural gas revenue in dollars per barrel is deducted from this figure, to establish the necessary minimum price for a barrel of crude oil. This procedure has many pitfalls. The prices of oil and gas are mutually dependent; it is misleading to think of holding one constant and allowing the other to vary in such a way as to achieve a desirable total revenue. If the price of either changes, both prices are likely to be altered. The main reason that Davis handled the problem in this way is of course the lack of satisfactory alternatives, but this should not obscure the arbitrary nature of the alternative he has chosen.

Davis then relates the price of crude oil (expressed in 1956 dollars) and the various projected returns to drilling in order to determine the price for crude oil at which producers will be willing to carry out an exploration program with a drilling return of x barrels per foot. It is, as Davis terms it, a "breakeven" analysis. Davis computes such a curve which will yield 10 per cent return on invested capital. Then he adjusts it upward. In his words, "Retaining the shape and slopes of the curve calculated, the curve was arbitrarily adjusted upward. There are indications that the price in 1956 was barely adequate to maintain incentive; therefore, the curve was shifted to pass through the point ($2.80, 12.6 barrels per foot)."[18] Such an adjustment implies that the breakeven return on investment is somewhat more than 10 per cent.

If drilling is curtailed by inadequate profits, by how much is it curtailed? Davis resorts to a rather ingenious expedient, unfortunately only briefly explained. Suppose that the price of crude oil cannot be increased. Then drilling will not be undertaken if the return is below the breakeven level. Suppose that the drilling return curve is already below this level, because so much oil has already been discovered. Will all drilling cease? No, says Davis, but the marginal producers will be forced to leave the field, and the decline in the rate of drilling will increase the average return. Davis then computes a curve showing the relationship between (a) the percentage reduction in the drilling rate, and (b) the percentage increase in the drilling return which is obtained by reducing the drilling rate.[10] The way in which this relationship was derived is not made clear, but it seems to be based on data giving some approximation to the productivity of drilling in various geological provinces, which would ideally consist of an array of the available drilling opportunities, ranging from the most productive to the least productive sites, as of a given moment, and showing how the average productivity would change as progressively more productive opportunities are eliminated in order to produce at the "breakeven" level, given the current price of crude oil.

But what is more puzzling is the problem which develops when one tries to reconcile the possibility of increasing the average drilling return by curtailing the current drilling rate, with the use of extrapolated "smooth" curves which relate drilling returns to total cumulative discoveries. These curves are monotonically decreasing, and the use of the functional relationship between the average drilling return and cumulative total discoveries admits of no equivocation. If we regard the extrapolated returns curve as a continuous function, its steady, unbroken decline is not consistent, it would seem, with the possibility of adjusting the drilling rate to increase the drilling return. If the latter is possible, then the drilling return may flatten out or even increase. This is an inevitable consequence of relating the drilling return to cumulative total discoveries.

It seems to the present authors that either of two solutions is possible, but not both. If the breakeven point is reached, and if the steadily decreasing returns curve is to hold, then the price of crude oil *must* increase. If the breakeven point is reached, and exploration attempts are correspondingly curtailed so as to increase the average return, then the returns curve *cannot* continue to decrease, but must hold constant or turn up. This is due to the fact that the returns curve is not related to the time rate of drilling, but to cumulative total discoveries. It may seem captious to stress this objection. One possible answer is that the returns curve only has a general downward trend, and might be reversed for a short time. However, this steadily decreasing curve is the very foundation of all of Davis's analysis[20] and any change in its direction would have to be quite temporary to leave Davis's major conclusions unchanged.

Since Davis places no small emphasis on the possibility of increasing the drilling return by decreasing the drilling rate, let us attempt to conceive of a situation in which it would be possible. Perhaps Davis looks upon the entire 1936-1956 record as having been achieved at a certain level of drilling intensity—say 95 per cent of drilling capacity or thereabout—given the state of technological knowledge and the availability of capital. Now let us look upon the situation as having changed drastically in the last few years. Perhaps a new level of drilling intensity is appropriate at, say, 70 per cent of existing capacity and that it is advisable to liquidate some equipment and thereby lower the capacity of the industry. Davis does not make it explicit, but perhaps his 1936-56 curve is based on the implicit assumption of, say, an eight per cent per year increase in total footage drilled, and perhaps if the rate of increase drops to one per cent an entirely different curve is appropriate. This does not seem likely unless altogether "too many" wells have been drilled in the past. If this be the case it would be difficult to account for except in terms of overoptimism on the part of operators, or of an "unnecessarily high" price for oil.

With this construction in mind, however, we can follow Davis's argument further. Suppose the breakeven point is reached, and price cannot be increased. Then operators lose their optimism, drillers sell their surplus equipment, the industry limits itself to a smaller number of more likely prospects, and the drilling phase of the industry shifts to an altogether different returns curve.

This may solve the immediate problem, but it raises many new questions as to the extent to which the rest of his analysis may have to be modified to account for the increase in returns gained by limiting the drilling rate.

Concerning the way in which Davis handles cost and revenue factors, and the rate of drilling, two concluding comments are necessary. First, it might be better to rely on the "availability of capital" approach which merely takes total revenue into account, and to ignore the rather tricky profitability question. This means, in effect, that price will *have to* increase when the drilling return falls to a level below the "breakeven" point. Failing this, production must be curtailed and lower-cost sources of energy supply substituted for oil. (This, in economic terms, is an acknowledgment of the fact that production must be curtailed when marginal revenue falls below marginal cost at the current rate of production.) The second difficulty is with the matching of receipts and expenditures. It is evident that Davis is speaking throughout of current expenditures on exploration; his costs are current-year outlays. But he also speaks of revenues as if they were contemporary with expenditures. The value of a well with reserves of 85,000 barrels is spoken of as being immediately comparable with its costs of exploration and development. Actually, there is a considerable time lag between the costs incurred and the revenues which are not realized until production is under way. There is no way of determining, from published data, how long the average time lag is between expenditures and the beginning of receipts for a given well. One gathers from indirect and informal sources that it is two years, three years, or perhaps often more. If it were possible to arrive at some average time lag, then the expenditures of one year might be compounded at an appropriate rate of interest and compared with the receipts beginning two or three years hence; or current expenditures might be compared with the discounted receipts beginning two or three years in the future. But to do this with any degree of accuracy, it would be necessary to have available a great wealth of detail concerning the production of a given year and its relationship to the original outlays of earlier years.

Now we are in a position to understand how Davis proceeds to predict the future productive capacity of the United States. He begins with the amount of crude oil reserves at the beginning of the year. Davis assumes that the oil industry will be extremely reluctant to produce at such a rate that reserves are less than ten years' supply at the current rate of production. It follows that production will not exceed ten per cent of reserves as long as the industry tends to look upon itself as a "going concern." On the other hand, the maximum efficient rate of withdrawal is about 12 per cent per year,[21] and rates above that level would be seriously wasteful.

Therefore, Davis takes beginning reserves, and multiplies them by ten per cent for earlier years, and by twelve per cent for years after the decline in the drilling return. This is then compared with the estimate of demand for the current year, and the lower of the two figures is taken as the production requirement after making an allowance for imports. Then total production, so estimated, is multiplied by the estimated price of crude oil, and the percentage change in total revenue is calculated relative to the preceding year. (Natural gas revenue is also included in the crude oil price, as an adjustment factor.)

The percentage change in drilling is estimated from the percentage changes in total revenue and in Gross National Product, according to the equation given above (page 17). One can then take last year's footage and multiply it by the change in drilling rate resulting from this equation, and the "uncorrected" current-year drilling rate is obtained. Following this step, the "profitability" calculation is made. Since total cumulative discoveries as of the beginning of the year are known, the drilling return in barrels per foot, for the estimated increase in total discoveries, can be determined. This will be, say, ten barrels per foot. Now reference to the "breakeven" curve will determine the minimum crude price for a drilling return of ten barrels per foot. If this is more than, or equal to, the prevailing crude price, there is no correction to the drilling return, or the "uncorrected" drilling rate. (If it is below the prevailing crude price, Davis would hold that the "uncorrected" drilling rate must be cut by a certain per cent to raise the return to the minimum level. This means that a lower level of discoveries will be made than was contemplated in the first step.)

The drilling rate is then multiplied by the drilling return to determine the addition to total cumulative discoveries. Deducting the yearly production, the net addition to reserves as of the end of the year is determined. This figure is then used to begin the calculations for the next year.

Davis then carries out 48 sets of computations for all the combinations of the following variables:

1. Drilling return: "best," "average," "worst"
2. Crude oil price: $3, $4, $5, $6
3. Productive capacity: ten per cent of reserves per year; twelve per cent of reserves per year
4. Demand: increasing at 1½ per cent per year; at 3½ per cent per year

These calculations generally show the United States reaching a peak of production sometime in the 1960's, although the use of the more favorable assumptions places the peak in the 1970's. Drilling follows the same pattern, although its peak comes a bit earlier. Peak production usually lies between nine and ten million barrels per day.

Davis carries out several other computations, showing the effect of changes in one or two factors with the others held constant. As the price of crude increases, the peak of production is delayed a few years, and the level of output at the peak is increased, but a steady decline inevitably follows. The effect of varying the drilling return has practically the same effect as varying the price, all other things being equal. Ultimate total discoveries, however, are considerably increased with high prices: with the "worst" return, the ultimate total discoveries are 140 billion barrels; with the "average" return, 160 billion; with the "best" return, 195 billion.

The techniques explored by Davis are interesting. The reader's chief regret stems from the lack of detail as to certain sources and methods, and from the absence of correlation coefficients and standard errors of estimate.

* * *

The fourth study is a regional study by R. E. Megill which concerns Oklahoma and Kansas.[22] This paper is notable for several methodological features. The author divides production costs into finding cost, development cost, and operating (producing) cost. These are the same three cost categories which have been adopted in the present study, and with one exception the definitions of these categories are identical with ours. The exception concerns the definition of finding costs, where Megill, like Struth, includes the costs of all dry holes in this category, whether the dry holes resulted from exploratory wells or from dry developmental wells.

Megill is chiefly interested in determining the magnitude of finding costs in the Kansas-Oklahoma region. He defines finding costs to include geological and geophysical costs, leasing costs (including lease rentals and the value of surrendered leases), and the cost of all dry holes drilled. In order to arrive at a dollar figure for finding costs, the author lists the following necessary items of information: the number of employed geologists and scouts (ascertainable from professional membership lists); the amount of geophysical effort expended (obtainable in terms of geophysical-crew-months from the records of the Interstate Compact Commission); the amount of undeveloped acreage held by the industry (obtainable from records of the Independent Petroleum Association of America); and the number of dry holes drilled (obtainable from trade journals).[23]

Megill gives data on the number of geologists, scouts, geophysical-crew-months, undeveloped acreage leased, and dry holes, and also gives total dollar cost figures, but unfortunately does not show how he goes from one to the other. Information is presented concerning the trend in reserve discoveries per exploratory well, for the period 1942-1957. Yearly changes in reserves are reallocated to the original year of discovery, and the revised estimates are corrected for future revisions, including future waterflood reserve potential, but the basis on which these corrections are made is not disclosed.

This paper also touches on the joint-cost problem. Recognizing that no acceptable method of allocating joint costs for oil and gas has yet been devised, the author makes the provisional assumption that "gas finding effort" is measured by the percentage of total successful wildcat wells which find gas. This term seems misleading to the extent that it suggests that there is a difference in motives present; it suggests that drilling is undertaken typically to find either oil *or* gas, rather than that the actual motive of search is to find both oil *and* gas.

In a second paper, the same author considers replacement costs for crude oil in two areas: the Illinois Basin, and the Michigan Basin.[24] Here he also emphasizes the distinction between finding, development, and operating costs. These are looked upon as the three components of "replacement cost" and are the current costs to the industry, at one specific point in time, of finding a barrel of oil, developing a barrel of oil, and producing a barrel of oil—but not the same barrel. Megill breaks down total costs in the following manner:

1. Finding costs: geological, geophysical, and leasing costs; all dry hole costs; value of surrendered leases.
2. Development costs: all drilling costs (successful wells), plus pumping and lease equipment for wells completed.
3. Operating costs: lease and well expense, plus miscellaneous overhead items.

This type of breakdown is useful for the purpose of computing replacement costs as defined above, which are not measures of current costs, but rather constitute a cost standard which can be compared with the current crude oil price.

* * *

The fifth study to be considered is the "Joint Association Survey of Industry Drilling Costs, 1955 and 1956," conducted by the American Petroleum Institute, the Independent Petroleum Association of America, and the Mid-Continent Oil and Gas Association.[25] Estimates of drilling expenditures for the years 1955 and 1956 cover "all drilling costs including the costs of equipping wells through the Christmas tree, but excluding pumping and lease equipment, flow lines and tank batteries, and exploration and leasing outlays."

The basis of the survey was a questionnaire mailed to all producers known by the three associations to be engaged in drilling oil and gas wells in 1955 and 1956. Replies were received from 203 producers with data covering 24.7 per cent of all wells drilled in 1955 and 23.5 per cent of all wells drilled in 1956. The costs reported by respondents were applied by areas and depths to non-reported wells. The fact that a high proportion of deeper wells was included in the replies is shown by the circumstance that the reported wells accounted for 34.0 per cent of all footage drilled in 1956. Since deeper wells are more costly, it is not surprising that the percentage of total drilling expenditures represented by the reported wells was still higher: 43.5 per cent in 1955 and 42.6 per cent in 1956. The report contains little information as to the representativeness of the sample, but it can be seen from the percentages given above that the average well reported by survey respondents was some 37.7 per cent deeper and 76.1 per cent more costly than the average well from the general population of wells drilled in 1955, and some 39.2 per cent deeper and 81.3 per cent more costly than the average well drilled in 1956. These considerations in themselves indicate that the wells reported were, in general, not typical wells as regards cost and depth.

Perhaps the casual reader of the Joint Survey would not be interested in the precise nature of the statistical techniques used in arriving at the estimates in their final forms. But in view of the unique nature of the data, and the importance of the problems requiring the use of the findings, it is unfortunate that the report does not include an appendix on sources and methods, with some indication as to probable margins of error, even if the latter were largely a matter of judgment.

The statistical tables appended to the report are presented in admirable detail: average cost, total cost, and footages are shown by depth of well, by states, and both states and depth ranges combined. Separate data are given for dry holes and for productive wells. A breakdown between tangible and intangible costs of drilling and equipping wells is also given, but unfortunately no definition is given for either of the categories of tangible or intangible costs. The cost of drilling offshore wells is shown by depth ranges.

Offshore drilling costs, when analyzed, reveal one noteworthy feature which would seem to merit some special comment in the report, although none is offered. This circumstance is the significantly higher average cost per foot for wells in the 5001-7500 foot depth range than for wells in the 7501-10,000 range. Other things being equal, it certainly does not cost less to drill deeper; indeed, the main conclusion of the survey is that average and total costs of drilling increase very rapidly with increasing well depth. Apart from some general remarks about "erratic fluctuations" in the section entitled "Accuracy of Estimates," the reader is left without any guidance concerning the interpretation of this apparent paradox. The reader must therefore content himself with conjectures as to possible differences in platform costs, assuming that the shallower wells were drilled in deeper water, and vice versa. Some comment upon this would have been in order, particularly since the earlier survey for 1953 showed a similarly unexpected decrease in average drilling costs per foot for precisely the same depth ranges.

The Joint Survey for the years 1955 and 1956 represents considerable improvement in data collection, classification, and presentation over the earlier study. However, the informational release on drilling costs is inadequate in these respects:

1. The lack of explanation of the methods used to estimate the various characteristics of the universe from the sample.
2. The lack of evidence of adequate sample design.
3. The unfortunate delay in the collection, compilation, and analysis of the data and in the release of the results.
4. Failure to relate costs to oil and gas found and produced.

• • •

The last study to be considered is that of C. C. Anderson of the United States Bureau of Mines.[26] Anderson has made a comprehensive survey of the available data on petroleum industry expenditures for exploration, development, and production, for the years 1948, 1951, 1953, and 1955. His study represents what is perhaps the most thoroughgoing attempt yet carried out to compile industry-wide statistics on the total dollar volume of current cash outlays for finding, developing, and producing fluid hydrocarbons. Considering the study on its own terms, it fails of being definitive only to the extent that the basic industry data sources are incomplete and imperfect. This is a source of error that is of unknown, but probably rather large, magnitude. Considering the study from the special frame of reference employed in the present monograph, two comments may be made.

First, the limitations inherent in current cash outlay statistics as guides to actual economic costs must be kept in mind. All current cash outlays of a given period are not necessarily indicative of costs incurred for the economic activities of that period. Payments may be made for obligations incurred in the past, or for productive activities which will benefit the operations of many succeeding time periods. The first of these qualifications is probably not very important in the oil industry, but the second is extremely significant. All good accounting systems distinguish between outlays for current expenses and outlays for items of capital investment. All cash outlays for current expenses should be considered as part of current total cost, but only that part of the capital outlay which contributes toward current production can be properly classified as a component of current total cost. Depreciation is the best example of a capital outlay being allocated among the years of productive life for the capital asset. If one is to make a compilation of current total costs incurred by the petroleum industry, it is imperative that the cash outlays for finding cost and for development cost be subdivided into their capital investment and current expenditure components and properly allocated to discoveries and production.

Second, Anderson does not relate the cost of finding, developing, and producing oil and gas to the number of physical units of oil and gas reserves actually found, developed, and produced. Instead, he makes a comparison of current dollar costs with current dollar revenues from the sale of oil and gas. The total cost of finding, developing, and producing oil and gas is deducted from the total net revenue from oil and gas production, the difference being referred to as the "net annual balance." This figure, however, bears no ascertainable relationship to the actual economic profit or loss made by the industry during the year. Not all the cash outlays expended represent current economic costs. Perfectly accurate profit and loss accounting would require not only the separation of costs into capital and current expenses, but also the allocation of these costs to the actual physical volumes of reserves discovered, developed, and produced. It is of course no criticism of Anderson that he has failed to do this, for at present the lack of data precludes any such computation.

II. RECOMMENDATIONS FOR CONDUCT OF A STUDY OF CRUDE OIL AND NATURAL GAS COSTS

THE procedures used to measure the costs of making additions to total cumulative discoveries of crude oil and natural gas will depend to a large degree upon the quality and comprehensiveness of the basic statistics which are available for use. The discussion which follows will first describe procedures which would be appropriate if complete information were available; then the discussion will describe the compromises which are necessary when only limited information is available.

Methodological Procedures: Complete Information Available

Let us assume that available data are reliable and sufficiently detailed to answer all computational requirements. Let us suppose that geologists and geophysicists, while not possessing omniscience prior to the drilling operation, can estimate the reserves that are discovered by successful exploratory wells with precision. Let us suppose further that all firms in the oil industry keep complete records on the cost of their operations, and that this information is available to disinterested research workers.

To start with the simplest possible case, take the instance of a firm which drills one well and discovers a small field consisting of a single oil pool. The complete exploitation of this pool, we shall assume, can be carried out by this single well. In this simple (and admittedly rare) case, we can easily identify the three basic categories of cost. First, there are the finding costs consisting of expenses incident to the obtaining of the lease, all geological and geophysical expenses relating to the well, and the costs incurred in drilling and completing the successful well and preparing it for production through the installation of the Christmas tree. Second, there are the development costs which include expenditures for flow lines, separators, storage tanks, and other items required as field auxiliaries to the completed well. The finding and developing costs together represent the firm's capital investment in the field as opposed to the operating or production expenses which make up the third cost category. These production costs include the expense of pumping (when necessary), field maintenance and upkeep items, and continuing expenses in connection with leasing.

To make this simple example highly concrete, let us suppose that the well discovers a reserve of one million barrels. Suppose that the costs incurred in developing this reserve are as follows:

	Year	*Amount*
Finding or Exploration Costs	1958	$ 500,000
Development Costs	1958	100,000
Production Costs	1959	100,000
Production Costs	1960	100,000
Production Costs	1961	100,000
Production Costs	1962	100,000
		$1,000,000

Suppose, further, that the production history of the well is as follows:

Year	*Production (bbls.)*
1959	400,000
1960	300,000
1961	200,000
1962	100,000
	1,000,000

In this example, the total cost of producing one million barrels of crude oil is one million dollars. However, the average cost is not correctly to be estimated at one dollar per barrel, because of the difference in the timing of outlays and of revenues. The significant item on the expenditure side is the *capital* outlay of $600,000 for finding and developing the pool, all of which is necessary to obtain production from the well during its four-year life. The firm has found it necessary to commit $600,000 in otherwise liquid funds for a period of four years in order to produce the oil. If the firm has borrowed these funds, it will pay an interest charge which must be included as part of the total capital cost. If the firm has used its own money, it must include the "opportunity cost" on these funds as part of the total capital cost, since the money might have been invested elsewhere. What is the meaning of this opportunity cost? It is the return foregone as a result of the decision to use the firm's own funds rather than to invest them elsewhere. This return can best be measured by assessing it as a percentage somewhat higher than that which could be earned in a perfectly safe investment. Government bonds can be taken as the criterion of the latter, with somewhat better than a three per cent return possible in 1957-58. For convenience, let us set the rate of opportunity cost at four per cent. The company drilling the well, therefore, has to invest $600,000 for a period of four years in order to produce one million barrels of crude oil.[27] The total cost per barrel of oil would therefore be $0.60 per barrel for the original finding and developing cost, and $0.096 per barrel for the interest charge. We can now compute the *average* per barrel cost for finding, developing, and producing as follows:

	Total Amount	*Cost per Barrel*
Exploration Costs (1958)		
Capital: principal	$ 500,000	$0.500
interest	80,000	0.080
	$ 580,000	$0.580
Development Costs (1958)		
Capital: principal	$ 100,000	$0.100
interest	16,000	0.016
	$ 116,000	$0.116
Production Costs (1959-62)		
Operating:	$ 400,000	$0.400
Total	$1,096,000	$1.096

The average total cost per barrel amounting to $1.096 is relevant when one considers the operating lifetime of the pool. But it is also necessary to know how the average cost per barrel will vary year by year over the life of the pool. Knowing the ultimate reserves in advance, we can compute the capital cost of each barrel as it is produced, and add to that the operating cost per barrel for the year in question. During the four years of operation, the pool's production is assumed to be carried out under conditions of increasing average production cost per barrel as the rate of production diminishes in the face of constant money outlays on production in each year. In practice, it is likely that operating expenses for pumping and secondary recovery would increase in later years. We have assumed that all capital costs are incurred in 1958, but it would be simple to allocate any subsequent capital outlays over the remaining total production units. (There is a theoretical question as to whether or not opportunity costs should be computed on subsequent capital outlays of this type, but this should not detain us here.) Under our assumptions, the average cost per barrel increases from year to year, as shown below:

	Capital Costs			
Year	*Finding Cost per Bbl.*	*Development Cost per Bbl.*	*Operating or Production Cost per Barrel*	*Average Total Cost per Barrel*
1959	$0.58*	$0.116	$0.250	$0.946
1960	0.58	0.116	0.333	1.029
1961	0.58	0.116	0.500	1.196
1962	0.58	0.116	1.000	1.696

*Sample calculation for 1959 finding cost:

$$\frac{\frac{400{,}000 \text{ bbls.}}{1{,}000{,}000 \text{ bbls.}} \times \$580{,}000}{400{,}000 \text{ bbls.}} = \$0.58 \text{ per bbl.}$$

Are these cost figures more meaningful than the single average cost per barrel that was obtained in the earlier illustration? There can be no doubt but that this latter set is more appropriate as a representation of the increasing total unit cost of the oil taken from the declining field. While this is the ideal way to view the time pattern of unit costs, it deserves re-emphasis that such a view is entirely dependent upon the very important assumption that total ultimate reserves discovered can be estimated with precision in the year of initial discovery.

Next, while still retaining the assumption of the availability of complete information, let us consider the more complicated case of the multi-well field. Again let us assume that the discovery well is the *only* well drilled by the firm which makes the discovery. Upon completion of the well, the geological and engineering staffs are able to ascertain the volume of reserves with precision. However, all of these reserves are not "proved," i.e., not fully recoverable through the first well. Further wells will be needed if all the oil is to be produced. Here we encounter the problem of accounting for discoveries in the three categories of new discoveries, extensions, and revisions. In a sense, the first well has accomplished the entirety of the exploratory task, since we assume that, once discovered, the boundaries of the oil field are known with certainty. This being the case, there will be no occasion for subsequent revisions of the capacity of the field. However, more development wells are needed to provide extensions to the reserves "proved" by the first well. The entire cost of development wells would be included in development (capital) cost.

To illustrate the simplest multi-well case, let us assume that an exploratory well is drilled at a total cost of $1,000,000. This well is successful and discovers a pool whose ultimate reserves are known to be ten million barrels of crude oil. However, the single well can only produce five million barrels because of reservoir conditions. A study of these conditions shows that three development wells can capture the remaining five million barrels; the extensions added by the three wells being three million barrels for the second well, one million for the third, and one million for the fourth. In the system of classification used by the American Petroleum Institute, the discoveries of the first well would be classified as five million barrels of "new discoveries," and the reserves made available by the next three wells would be classified as five million barrels of "extensions."

Let us assume further that imperfections in the capital market prevent the field operator from drilling all three developmental wells immediately. Instead, he is forced to finance his subsequent drilling in part of the receipts from his oil production, so that he drills one additional development well per year for three years. His total reserves could then be produced over a period of ten years, as follows:

Year	Discovery Well Production	Developmental Well Production			Total Prod.
		No. One	No. Two	No. Three	
	thousands of barrels				
1958	–0–				–0–
1959	1,000				1,000
1960	800	900			1,700
1961	700	600	300		1,600
1962	600	500	100	300	1,500
1963	500	200	100	200	1,000
1964	400	200	100	100	800
1965	400	200	100	100	800
1966	300	200	100	100	700
1967	200	100	100	100	500
1968	100	100	100	100	400
	5,000	3,000	1,000	1,000	10,000

Assumed cash outlays corresponding to the assumed production schedule are given below:

Year	Exploratory (Capital) Cost	Development (Capital) Cost			Production (Operating) Cost
		Well No. 1	Well No. 2	Well No. 3	
1958	$1,000,000				
1959		$200,000			$ 100,000
1960			$200,000		170,000
1961				$200,000	192,000
1962					225,000
1963					250,000
1964					280,000
1965					300,000
1966					350,000
1967					350,000
1968					400,000
	$1,000,000	$200,000	$200,000	$200,000	$2,617,000

To find the average cost per barrel produced, we proceed as before. We add opportunity cost to the capital outlays. For the exploratory well, it is four per cent for ten years on one million dollars, or a total of $400,000. For the developmental wells, it is four per cent of $200,000 for nine, eight, and seven years respectively, or $72,000, $64,000, and $56,000. The total capital cost for the exploratory well,

$1,400,000 is allocated over the ten million barrels which the successful well has discovered. Hence, the per barrel cost of exploration is $1,400,000/10,000,000 bbls., or $0.14 per barrel. For the development and production costs, we add together the relevant capital and operating costs, as given below:

Development Cost	
Capital: principal	$ 600,000
interest	192,000
	$ 792,000
Production Cost	2,617,000
Total Production and Development Costs	$3,409,000
Development and Production Costs per barrel	$ 0.3409
Exploratory Cost per barrel	.1400
Average total cost per barrel	$ 0.4809

But it is no less true here than it is in the case of the one-well field that the average total cost over the life of the field is much less important than the average cost per year as production declines. Given our assumptions, we can easily compute this average yearly cost. As before, exploration cost is constant at $0.14 per barrel, being prorated over the entire ten million barrels discovered by the original well. Development and production costs for all wells producing in a given field in a given year are computed as the sum of (1) development cost (including opportunity cost), prorated over the total number of barrels of "extensions" added by the development wells drilled in the given year; and (2) production cost for the given year. Thus, in 1960, the first development well begins to produce. Its total capital cost is $272,000, and its extensions amount to three million barrels; hence, the development cost per barrel for this well is $0.0906. Production cost in 1960 amounts to $170,000. This is prorated over the total production from both wells in 1960, a total of 1,700,000 barrels. Hence the production cost per barrel is $0.10, and the total of the developmental cost and the production cost per barrel for that year is $0.1906. Add to this the constant exploratory cost per barrel of $0.14, and the total of all costs per barrel in 1960 is $0.3306. On this basis, the average costs per barrel for the whole life of the field may be computed as shown in the table below:

		Development Cost Per Barrel				
Year	*Exploratory Cost per Barrel*	*Well No. 2*	*Well No. 1*	*Well No. 3*	*Prod. Cost per Bbl.*	*Total Cost per Bbl.*
1959	$ .14				$ .100	$0.2400
1960	.14	$ .0906			.100	0.3306
1961	.14	.0906	$ .264		.120	0.6146
1962	.14	.0906	.264	$ .256	.150	0.9006
1963	.14	.0906	.264	.256	.250	1.0006
1964	.14	.0906	.264	.256	.350	1.1006
1965	.14	.0906	.264	.256	.375	1.1256
1966	.14	.0906	.264	.256	.500	1.2506
1967	.14	.0906	.264	.256	.700	1.4506
1968	.14	.0906	.264	.256	1.000	1.7506

This is as far as we can profitably go with the present simplified example. It indicates how the problem of cost allocation would be handled in the event that ideally adequate statistical information were available. At the cost of repetition, let us outline the procedure to be followed in such an instance, where a single exploratory well discovers a field that must be developed by additional wells:

1. Computation of per-barrel exploration cost:
    a. Add together the cost of lease acquisition, all geological and geophysical expenses, and all costs of drilling and completing the exploratory well up to the installation of the Christmas tree.
    b. Divide this total by the number of barrels of reserves discovered. Where complete information is

assumed, this will be the total barrels of (1) new discoveries "proved" by the exploratory well; and (2) extensions "proved" by later development wells. (Where information is imperfect, the total will also include revisions of earlier estimates of "proved" reserves.) This quotient would then be the exploration cost per barrel.

2. Computation of per-barrel development cost:
   a. For exploratory wells, development costs would include field development expenditures for flow lines, separators, storage tanks, etc. Add the cost of these elements together; compute opportunity cost for the total productive life of the exploratory well and add it to the previous total; then divide by the number of barrels of reserves discovered (see 1.b.).
   b. For developmental wells:
      (1) Developmental cost would include the relevant elements in 1.a. and in 2.a. above. (Generally there will be few additional costs of lease acquisition or for geological and geophysical service, relative to those involved in the drilling of the discovery well. In the present case, the assumption was that no such costs were incurred.)
      (2) The total cost would then be increased by the opportunity cost, computed for the total producing life of the development wells.
      (3) The total of (1) and (2) would then be divided by the number of barrels of "proved" reserves added through extensions; this quotient would then be the development cost per barrel.
3. Computation of per-barrel production cost:
   a. Add field maintenance and upkeep costs, pumping

costs, and continuing expenses in connection with leases.

b. Divide this total by the number of barrels of crude oil produced in the current year from all producing wells, exploratory and developmental together.

This is the recommended method for arriving at per-barrel costs under conditions of ideally adequate information. What compromises in method must be made when we move, by successive approximations, to more realistic cases? We will next investigate the ways in which the following complications will modify the ideal approach: (1) unsuccessful exploratory outlays; (2) developmental dry holes; (3) the relationship of estimates of extensions, revisions, and new discoveries, to industry activity in past, current, and future years; and (4) the allocation of joint costs between discoveries of crude oil, natural gas liquids, and natural gas.

METHODOLOGICAL PROCEDURES: INCOMPLETE INFORMATION

(1) *The problem of accounting for "unsuccessful" exploratory outlays.* A single firm may in a particular year make considerable outlays for acquiring leases, conducting geological and geophysical surveys, and drilling a number of exploratory wells, the great majority of which are likely to be dry holes. For successful exploratory wells, the assignment of the relevant drilling costs is straightforward, and the determination of the relevant leasing costs is equally straightforward. But the unsuccessful exploratory outlays are also a real cost of discovering the proved reserves found in that year. For the firm, it is true in a certain sense that its total exploratory outlay is necessary for the acquisition of those new crude reserves that it finds. This is true in the sense that, as long as oil finding remains in large part a fortuitous event,

a certain number of unsuccessful trials will be necessary for each successful discovery, and the larger the total number of trials, the greater will be the probability that the successful trials will bear a constant ratio to total trials, if success is actually based to a large extent on some mechanism of chance. (The ratio can be conceived of as constant over a relatively short period of time, such as a year; it is likely that over longer intervals of time, the ratio may decline.) Suppose the company in question drills twenty wells and only two find oil. It is meaningful to say that the total exploratory outlay for all twenty wells is necessary to accomplish the two discoveries, but how much of the outlay should be allocated to *each* of the successful wells is a completely indeterminate question. For the individual firm (assuming more than one successful exploratory well), the allocation to individual successful wells of the exploratory cost of some number of unsuccessful wells nearest the successful ones, will be an inescapably arbitrary procedure. The most nearly unbiassed procedure might be to prorate total "unsuccessful" exploratory outlays among successful wells on the basis of the relative volume of estimated ultimate reserves of each well, although there is no compelling reason to believe this is the only defensible procedure. All we can say in this instance is the following: if chance does largely determine the success of exploratory outlays, then the greater the number of exploratory wells drilled (both dry and productive), the more likely the total-reserve-based estimate is of being unbiassed.

It is precisely this circumstance which reduces the magnitude of the problem as far as our present purposes are concerned. We are interested primarily in costs on the national and regional levels. Our discussion has centered around the individual firm simply in order to express the problem in its most elementary terms. Fortunately, the complications inherent in accounting for unsuccessful exploratory outlays at the national and regional levels are less formidable. Still assuming that data on total exploratory outlays (both successful and unsuccessful) are available for the entire nation, take the total of these outlays and prorate it among the successful exploratory wells on the basis of their estimated ultimately recoverable reserves. This total exploratory cost should then be increased by the opportunity cost. All we have done, therefore, is to substitute the national average capitalized exploratory cost per barrel for the year, for the averages of individual companies whose particular experiences might individually be atypical of the national picture. Here, we are recognizing the limitations of the available data in another way. If we had separate data on the total exploratory costs of all successful wells, and of all unsuccessful wells, we could allow specific identification for the successful wells, and then somehow allocate the unsuccessful wells component among the successful wells. But since we are really interested only in national—or at most, regional—averages, this refinement, even if capable of being carried out, would not be worth the trouble.

(2) *The problem of developmental dry holes.* We must recognize that the relationship between exploratory and developmental wells is not as clear-cut as one might prefer to assume. In general, there is a qualitative difference between exploratory and developmental wells. Exploratory wells have higher risks of failure, and, when successful, result in making additions to proved reserves through the category of "discoveries of new fields and new pools in old fields," or

"new discoveries" as we have been referring to it. Developmental wells have lower risks of failure, and when successful, result in making lateral extensions to the reserves of known pools, and this addition to total reserves is classified under "extensions."

That a developmental well should frequently result in a dry hole should not be surprising. Given a condition of imperfect reservoir information, the drilling of dry developmental wells is just one cost of reservoir development, i.e., the cost involved in defining the boundaries of the reservoir. That an exploratory well should occasionally result in serving the function of a developmental well, i.e., that it should result in a long lateral extension of a known pool (more than one-half of a mile distant) is no more surprising; it merely reflects the arbitrary element in the definition of an exploratory well.

How do these two possibilities complicate the cost-estimation picture? First, we will consider dry developmental wells. At the level of the individual firm, drilling developmental wells in a known field, the cost of dry development wells is obviously part of the "development cost" for the reserves developed in the field. The best solution would be to include the costs of dry development wells drilled in a certain year along with the cost of the successful development wells drilled in that same year as capitalized developmental costs to be allocated to extensions to known reserves. Here the solution is arbitrary at the level of the individual firm, but it is much less arbitrary than in the case of unsuccessful exploratory wells, because any developmental well is always drilled in connection with a particular pool, which can be used as a basis for the accounting. Exploratory drilling, need-less to say, is characterized by the fact that it is not oriented with regard to any known pool (except for the case of "outpost" wells, to be explained below).

Here, the principle of allocation is more easily justified. But the practice is more difficult. An unsuccessful development well increases the per-barrel costs of producing from the whole pool, the limits of which it has helped to define. There are several possible ways of allocating development costs of unsuccessful development wells.

(a) The motive behind the development well is the search for *extensions* to proved reserves. A case could be made for allocating the capital costs to all past and future successful developmental wells, the allocation being on the basis of relative volume of extensions for each successful developmental well. Although this is defensible in theory, in application it would prove much too burdensome to be continually readjusting all unit costs for each producing well, each time another developmental well turns out to be dry.

(b) It would be more practical to let the developmental well activity of each year stand by itself. Thus, the costs of current dry developmental wells would be allocated among successful developmental wells, on the basis of total extensions per successful well; but the allocation would only be among the successful developmental wells drilled in the same field *in the same year* as the unsuccessful wells. The reason for preferring this measure (apart from its greater ease of calculation) is that it corresponds, on the individual firm level, to the figure which is desired at the national level. For the nation as a whole, the search for extensions is a very meaningful concept, and the success of this search can be measured by the ratio of the total cost of developmental wells drilled during the year (both unsuccessful and successful) to the total number of barrels of reserves gained through extensions.

(c) One obvious area of difficulty remains, at least on the level of the individual firm. Suppose that, in a given year, all developmental wells are dry, so that there is no successful well to absorb these costs. The firm should keep the cost of all dry developmental wells for purposes of national reporting; for its own records, it might adopt either of two essentially makeshift procedures: (1) It might set up an account for "current dry development hole costs" as a separate component of operating costs, and charge this cost to current production; or (2) it might consolidate this cost with that of the preceding or the following year, when successful development wells were drilled or may be drilled. This would necessitate the recomputing of the costs for at least one year, and is generally undesirable—but there seems to be no really suitable solution, short of adopting method (a) above, and revising the cost for all developmental wells.

Our proposal is therefore to take all developmental costs, for dry as well as productive developmental wells, and divide the total by the number of barrels of extensions for a given year in order to arrive at a national average. This contrasts with the treatment of Struth, among others, who regards dry developmental wells as exploratory costs. Reasons for disagreement with his view have been outlined in Section I, but it may be profitable to consider them again in this particular context, and to emphasize the usefulness of maintaining a distinction between exploration and development costs. Dry development well costs should not be considered part of exploratory costs, because they are not comparable with exploratory wells proper on either a cost or a risk basis. First, there are not many purely geological and geophysical costs associated with dry development wells, so cost structures are incommensurate. Second, development wells have a much lower dry-hole ratio, so that the very high risk element peculiar to exploratory drilling is not present. Third, and most important, the success of exploratory wells in a given year influences to a great extent the success of developmental wells in succeeding years, particularly if large fields are discovered by the exploratory wells in the given year. There can be no reasonable doubt that the discovery of a large field in one year lowers the cost of developing and producing reserves associated with that field in the succeeding years. It is a principal task of this analysis to describe a method by which this reduction of succeeding average costs can be measured, if the necessary data are available. This is, to be sure, the chief methodological reason for maintaining the distinction. Failure to do so by including developmental dry holes as exploratory costs results in the following distortions: (a) it overestimates the amount of drilling done at the typical exploratory risk of about eight to one; (b) it underestimates the discoveries per true exploratory well, by including all developmental dry holes which by definition added nothing to discoveries; (c) it conceals variations in exploratory well success rates by failing to allow for changes in the ratio of development wells (and hence of dry development wells) to exploratory wells proper.

Having considered dry developmental wells, let us now turn to the problem of exploratory wells that succeed in performing developmental functions, i.e., making extensions laterally to known pools. To explain this phenomenon, it is desirable to take another look at the definition of exploratory wells. An exploratory well must be at least one-half of a mile from the nearest producing well, where formations are very indefinite. If formations are very definite in outline, it must be up to two miles away from the nearest producer. Suppose that the formations are indefinite, but that there is a suspicion that a given pool extends laterally more than one-half of a mile from the nearest producer. In this case, the development of this pool will be achieved by an exploratory well called an "outpost" (or extension test), and the well will be listed as an exploratory well even if it were "certain" to be a successful extension. The "outpost" is then the link between exploratory and developmental wells. If dry, it is exploratory; if successful, it is very likely a developmental well in actuality, and its reserves are included in extensions, rather than new discoveries, although the well itself is listed by Lahee as an exploratory well. (On the other hand, if an outpost discovers a deeper or shallower pool, rather than a lateral extension to the old pool, then it is a "new pool" wildcat and is properly considered an exploratory well. For a complete classification of exploratory wells, see Table I.)

Is an outpost well "really" an exploratory well, or is it "really" a development well? It is in the nature of an exploratory well to the extent that its risk of failure is higher, and its cost structure is greater than that of the typical developmental well. But it depends upon the individual well—some outposts might be much closer to the average developmental well in terms of cost and risk.

The fact that some genuinely exploratory efforts (the outpost wells) succeed only in extending old pools should probably be ignored. If, on the other hand, we wish to adhere to

TABLE I

CLASSIFICATION OF EXPLORATORY WELLS[28]

	Classification When Drilling Started	Classification after Completion or Abandonment	
		Successful	Unsuccessful
	A	B	C
Drilling for long extension of pool partly developed	1. Outpost	1. Extension well (sometimes new pool discovery)	1. Dry outpost well
Drilling for new pool on a structure or in a geological area already productive:		New-pool discovery wells	Dry new-pool tests
New Pool Tests:			
1. Drilling within limits of pool a. For new pool above deepest pool	2a. Shallower-pool test	2a. Shallower-pool discovery well	2a. Dry shallower-pool test
b. For new pool below deepest pool	2b. Deeper-pool test	2b. Deeper-pool discovery well	2b. Dry deeper-pool test
2. Drilling outside limits of developed pools	2c. New-pool wildcat	2c. New pool discovery wildcat (sometimes an extension well)	2c. Dry new-pool wildcat
Drilling for a new field (i.e., on a structure or in an environment never before productive.)	3. New-field wildcat	3. New-field discovery wildcat	3. Dry new-field wildcat

our insistence that the pool is the basic unit in accounting for per-barrel costs, then the outlays for the outpost wells should be considered as developmental costs that contain an element of exploratory expense, and we would be forced to adopt some such measures as crediting the additional exploratory expense involved in "rediscovering" the pool back to the original year of discovery, with some discount factor applied because of the time factor of the cost outlay. However, this expedient would be too cumbersome and arbitrary in application; in general, it would always seem a distinctly risky procedure to make inter-temporal revisions in money costs. There is also another reason for ignoring the developmental nature of some outpost wells. Statistical data on the drilling of exploratory wells (number of wells, total and average footage, etc.) are available on an acceptably comparable basis since 1937; these statistics include outpost wells, and if the latter were assumed to make a negligible contribution to field development, these statistics could be used in their present form for the purpose of estimating certain indexes of the productivity of exploratory drilling. Precisely how will the results be distorted by this simplifying assumption? The intention is to divide a measure of exploratory drilling activity (dollars, wells, footage, etc.) by the total number of barrels of new discoveries, in order to arrive at an approximation of the cost per barrel of discovering new reserves during a given year. Some of these "exploratory" wells, however, will be such only by definition, and will actually contribute to the development of a previously discovered pool. By employing this treatment, we overstate somewhat the exploratory costs per barrel in that year, and by leaving the cost of the extension outpost well out of the total cost of development wells, we understate somewhat the per barrel development costs of the pools in question. This is unfortunate, but at least there is the possibility that the errors will tend to offset one another. Year-to-year comparability would be enhanced if exploratory outpost extensions to old pools remained at a more or less constant percentage of total extensions, but it seems more likely that in years of high new-field discoveries, the exploratory extensions that follow over the next few years would be relatively larger.

(3) *The problem of relating estimates of extensions, revisions, and new discoveries, to industry activity in past,*

current, and future years. This problem arises because of imperfect knowledge concerning the extent of newly discovered reserves, and it must be dealt with in terms of the categories used by the American Petroleum Institute and the American Gas Association in measuring proved reserves. These annual estimates distinguish between drilled proved reserves and undrilled proved reserves. Drilled proved reserves refer to the volume of recoverable oil in that portion of a pool which is estimated to be recoverable by the production systems currently in operation, with or without fluid injection, from the area actually drilled up on the spacing pattern adopted in the pool. Undrilled proved reserves are those which lie under undrilled spacing units which are so close and so related to the drilled units that it is considered highly probable that they will produce when drilled. Potential reserves recoverable by fluid injection methods are regarded as proved only after testing by a pilot plant, or after operation of an actual installed fluid injection process has confirmed recovery expectations. The intent is to err, if at all, on the side of conservatism. The American Petroleum Institute has access to original geological and geophysical estimates. The classical volumetric approach for determining the production potential of a reservoir is the formula[29]

$$R = FA\,(tspr)$$

R is recoverable oil in 42-gallon barrels
F is 7758 (the number of 42-gallon barrels per acre-foot of void space in the reservoir rock)
A is the subsurface area of the reservoir in acres
t is the average thickness of the reservoir in feet
s is the percentage of porosity of the reservoir rock
p is the percentage of saturation of hydrocarbons
r is the percentage of expected recovery.

In this formula, extensions to *R* can come about from increases in *A* as more wells are drilled and the pool is extended in areal extent, from re-estimations of *t*, *s*, or *p* as further drilling provides a more complete picture of the potentialities of the pool, and from changes in the catch-all factor *r*, which depends upon technological development in methods of production, the physical characteristics of the reservoir, and the economic horizon of production, which is dependent upon at least an implicit forecast of the future price structure. A conservative bias is introduced by the assumption that no technological progress in the direction of cost-reducing recovery techniques will be introduced during the life of the pool. In making the estimate, a fixed price for crude oil (the current price) is usually assumed, and this will be a conservative factor if the crude oil price rises relative to outlay costs in the future.

Let us take the example of a single successful exploratory well and use it to demonstrate how the geological definition of proved reserves is employed in order to record the volume of oil actually to be added to cumulative total discoveries as the result of the drilling of this successful well.

In the first year (the year of discovery), estimates will be made of all the factors included in the production-potential formula. How accurately will this initial year estimate measure the ultimate volume of reserves discovered by this well? How long will it be before a reasonably accurate estimate can be made? No perfectly definitive answer can be given until the well has finally been abandoned; our question is rather an inquiry into how long it will be before the statistics on reserves reflect reasonably well the amount of reserves added in the year the well was drilled. The first year's estimate will be entered in the statistics on reserves as "discoveries of new fields and new pools in old fields." This initial estimate will generally be quite conservative. Only a small areal extent is likely to be allocated to the well as drilled proved reserves; the amount estimated depends upon the complexity of the geology, with more complex formations being assigned smaller drilled proved reserves. Rarely will any undrilled proved reserves be attributed to a single well, these being credited to undrilled interstices between developmental wells in a developed field. From this point on, extensions and revisions will be credited to the successful exploratory well in following years as the original conservative estimate is revised upward. All of these subsequent extensions and revisions were in a sense "discovered" in the initial year.

Increases in the original reserve estimate could come about from changes in any of the factors mentioned in the volumetric formula given above. In fact, the major increases in reserve estimates for a given pool have come about through subsequent extensions to the originally estimated areal extent of the pool because of developmental drilling following the original discovery well, and through revisions of the original estimates as more information on thickness, porosity, and permeability is obtained or inferred from the records of the early production by extrapolation along that type of production decline curve which is considered applicable.[30] Revisions also arise when the installation of secondary recovery facilities is undertaken. Extensions and revisions due to these factors are quantitatively more important than those directly attributable to other technological reasons or market factors, although these factors are certainly not mutually exclusive.

If successful developmental wells are drilled in our hypothetical field, the total proved reserves of the field will be increased by the amount of extensions which have been deemed proved by the development wells. These extensions may consist of both drilled proved reserves and undrilled proved reserves. How should the effect of the increased reserves on costs be taken into account by the statistical records? This should be done by the same procedure which we followed in our earlier, simpler cases where complete knowledge was assumed from the outset. By the time the development wells have been drilled, two types of cost have been incurred: the exploratory costs for the original well, and the cost outlays for the developmental wells. Two reserve figures have been obtained: new discoveries, and extensions. The way to handle the problem is to add extensions to new discoveries and use the total figure to compute per-barrel exploration costs; this means that, as new extensions are being made in future years, the per-barrel exploration cost must be re-computed and will continue to decline as long as extensions are being made. (This is the same measure as was used in the simplified example, except that the "correct" per-barrel cost is approached by successive yearly approximation as the ultimate size of the field becomes more completely known.)

As far as per-barrel development costs are concerned, we must make a concession to the practical limitations of statistical sources. Per-barrel development cost must be computed on a yearly basis, rather than well-by-well, as was assumed in the simplified example. This is because extensions and revisions are meaningful on a pool basis (and the pool is the unit of discovery) but are virtually meaningless on a well-by-well basis. Hence we will have to give per-barrel development costs the following treatment: take the total cost of all developmental wells and divide this figure by the total number of barrels of extensions made by these wells during the year; this will be the per-barrel development cost for the year. The distinction between development and production costs must be maintained.

Production costs should be totalled separately and divided by the number of barrels of oil actually produced in the current year, in precisely the same manner as was illustrated in the earlier example.

Now suppose that the pool under consideration has ceased to grow through extensions because no further developmental wells have been drilled; nevertheless, the production record over the years is such as to indicate that earlier reserve estimates were too conservative. Furthermore, secondary recovery facilities have been installed and this also increases the productive potential of the pool. Additions to proved reserves would be registered in both cases as "revisions to prior year estimates." How are we to handle the additional costs and the additional reserves resulting from the element of revisions?

As far as the reserves themselves are concerned, the procedure is clear. The additional barrels should be credited back to the year of original discovery in order to compute more accurately the per-barrel exploration cost for the pool. As in the case of the relationship of extensions to per-barrel exploration cost, this will mean an annual recomputation of the per-barrel cost as long as revisions are being made in the reserve estimates. Here, too, the treatment is consistent with that of the simplified example, with the "correct" per-barrel cost being gradually approached as extensions and revisions are gradually added to the original estimate.

As far as the costs of making revisions are concerned, the problem is less capable of a satisfactory solution. For extensions, the relationship of added reserves to added costs is direct, and the per-barrel development cost measures the cost of making these extensions reasonably well. For revisions, the relationship of added reserves to added costs is much less direct, and the costs themselves are much smaller, consisting perhaps of outlays for secondary recovery installations, the current operating costs of such installations, and other auxiliary expenditures to confirm revision estimates such as core drilling and the like. Some of these costs will be included in development costs (the secondary-recovery installations) and the others will be current operating costs, to be included in production costs. Since the costs are relatively small, and since they are closely related in purpose to true development costs, it is probably the best alternative simply to leave these costs in these two categories of development and production costs. It is likely that most costs incurred for the knowledge necessary to revise the estimates will have been incurred primarily for other purposes.

A numerical example should now be introduced in order to illustrate the way in which an individual firm would compute its costs as outlined above, given that imperfect knowledge prevails as to ultimate reserves.

Let us assume that in 1958 an exploratory well costing $300,000 is drilled, which discovers new reserves initially estimated at one million barrels. In 1959, a developmental well is drilled at a cost of $100,000 resulting in extensions of one million barrels. In 1960, no further drilling is undertaken, but revisions of one million barrels are added to the original estimate. In 1961 and 1962, production continues with only current production costs being incurred, and the pool is exhausted by the end of 1962. The production of the pool follows this pattern:

Year	Production in Thousands of Barrels From Discovery Well	From Developmental Well	Yearly Total
1958	0		0
1959	600	0	600
1960	500	500	1,000
1961	400	400	800
1962	300	300	600
	1,800	1,200	3,000

The costs incurred follow this pattern:

Year	Exploration Costs (Capital)	Developmental Costs (Capital)	Production Costs	Total Cost
1958	$300,000			$300,000
1959		$100,000	$ 50,000	150,000
1960			100,000	100,000
1961			100,000	100,000
1962			150,000	150,000
	$300,000	$100,000	$400,000	$800,000

As of 1959, the per-barrel cost would be based on an exploration cost of $300,000 divided by the discoveries estimated at two million barrels as of that date. The production costs would be $50,000 divided by the current output of 600,000 barrels, or $0.083 per barrel. Development cost of $0.10 per barrel ($100,000 divided by extensions of 1,000,000 barrels) would not be recorded until the development well actually began to produce in 1960. (We are ignoring opportunity cost in this example in order to reduce the complication as much as possible.) Then as of the end of 1959, the cost estimates would be: exploration cost per barrel, $0.15; production cost per barrel, $0.083; total cost per barrel, $0.233.

As of 1960, with the revision to total discoveries, the per-barrel exploration cost would fall to $0.10 ($300,000/3,000,000 barrels), and the estimate for 1959 would be revised accordingly. As production begins from the developmental well, development costs of $0.10 per barrel would be attributed to those reserves produced from the one million barrels of extensions. The ideal way to account for these costs would be on a specific identification basis, barrel-by-barrel; but since it will no doubt be impossible in practice to determine whether or not a barrel of production comes from new discoveries, extensions, or revisions it would probably be best to allocate these costs against the *first* one million barrels produced from the developmental well. (More complex procedures would have to be devised for more complex pool conditions, such as multiple development wells.) An element of arbitrariness is inescapable. Note what this means: we have exploration costs per barrel applicable to *all* barrels currently produced from the pool, but the development cost per barrel is applicable only to those barrels produced from extensions. Hence, the average total cost of exploration and development per barrel is not the sum of average exploration cost and average development cost. Instead, the average development cost must be multiplied by a coefficient which shows the ratio of production from extensions to total production, and then this "corrected" average development cost can be added in with the other components of per-barrel costs. The procedure is illustrated in the example below, showing the 1959 figure as revised, and all other cost statistics for the life of the pool:

		Development Cost per Barrel				*Total Cost Per Barrel (2) + (5) + (6)*
Year	*Exploration Costs per Barrel*	*Unadj. Costs per Barrel*	*Ratio of Prod. from Extensions to Total Production*	*"Corrected" Development Costs*	*Production Costs*	
(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*	*(7)*
1959	$0.10				$0.083	$0.1830
1960	0.10	$0.10	.500	$0.0500	0.100	0.2500
1961	0.10	0.10	.500	0.0500	0.125	0.2750
1962	0.10	0.10	.167	0.0167	0.250	0.3667

It can be shown that total outlays for discovering, developing, and operating the field, amounting to $800,000, are fully allocated to the ultimate production of 3,000,000 barrels if the total cost per barrel for each year is applied to the production for each year. This is possible at the individual firm level if the pool records are kept in the manner outlined.

How could the records for individual pools kept in this manner be aggregated to arrive at national totals? Before answering this question, we must distinguish between two forms of the data for per-barrel exploration cost and per-barrel developmental cost. The first form of the per-barrel exploration cost series is the historical time series for per-barrel exploration cost which will be continually revised downward in the light of subsequent extensions and revisions. For example, the series might be revised in this way:

Year of Discovery	*Exploration Cost per Barrel for the Year of Discovery on the Basis of Knowledge Available in the Current Year Shown*					
	1950	*1951*	*1952*	*1953*	*1954*	*1955*
1948	$1.00	$0.90	$0.80	$0.70	$0.60	$0.55
1949	2.00	1.70	1.50	1.40	1.30	1.25
1950	3.00	1.95	1.85	1.80	1.75	1.70
1951		2.80	2.60	2.50	2.50	2.50
1952			3.10	2.10	2.00	1.75

The second form of the data for per-barrel exploratory cost is a series which expresses exploratory costs for each year in terms of each year's production. This is the series which is relevant to the study of trends in industry profits. This series will be computed in the following way: take the distribution of current-year production, in barrels, according to the year of pool discovery. Multiply the production in barrels for each original-discovery year by the current estimate of the exploration cost per barrel for the year of discovery computed on the basis of current year knowledge. Divide the total cost thus obtained by the total number of barrels currently produced, and the result will be the weighted-average exploration cost for all oil produced in the current year. In this connection it is necessary to point out that: (1) The data needed for such a calculation are apparently actually available.[31] (2) It would be necessary to include opportunity cost as a part of the exploration cost; this is particularly necessary when averaging data which may be taken from a time range of more than 50 years. (3) Some allowance must be made to reflect the effect of price changes. The problem of price change poses another enigma. Perhaps the best expedient would be to compute two series for historical exploration costs: one in terms of original or "historical" costs; the other in terms of current-dollar "replacement" costs developed by the use of an appropriate price index.

Now to distinguish the two series for comparable uses for per-barrel development cost. The first series is the historical series which is unlike the per-barrel exploratory series, in that it is not continually revised from year to year. Each year stands by itself: the cost of extensions is computed only once for the historical record and is not adjusted for subsequent revisions because of the formidable difficulties involved. The historical series is useful for time series comparisons and projections into the future.

The second form is the per-barrel developmental cost for all oil actually produced during a given year. Here, too, this series is the relevant one for the study of profit trends. This series is computed in precisely the same way as that for per-barrel exploratory cost: take the distribution of current year production from extensions of past years, measured in barrels, according to the year of the extension. Multiply the production in barrels for each extension-discovery year by the historical development cost for the year of extension. Divide the total cost thus obtained by the total number of barrels currently produced from past extensions, and the result will be the weighted-average per-barrel development cost for all oil produced in the current year from past extensions. Unlike the corresponding figure for exploration costs, however, this figure cannot be added to other costs to determine total current exploration and development costs. First, it must be adjusted by a correction factor which is the same as that employed in the related single-pool example. Take the weighted-average figure just obtained and multiply it by the ratio of current production from past extensions, to total current production. This corrected figure can then be added to the per-barrel exploration costs. Here, too, it is well to point out that: (1) It is necessary to include opportunity cost in the historical per-barrel developmental cost. (2) An allowance must be made for price changes; two series should be computed, one with and one without the price-index adjustment, and the results compared. (3) No revisions are made yearly in this historical series. (4) The data for making the current-year comparison figures are apparently not available; i.e., there is apparently no information as to the distribution of current production from past extensions, according to year of the original extension. This may necessitate treating per-barrel developmental cost in the same way as per-barrel production cost, as far as the current-year profit comparison figure is concerned. (This will be further discussed below.)

The third component of cost, per-barrel production, is fortunately the same for both uses. "Historical" production costs are, of course, used both for plotting time trends, and for measuring the impact of these costs on current profits. There is no tedious data-processing problem involved. All that is necessary is that operators should segregate these current expenses carefully; the reported figures can then be totalled and divided by current-year production.

To take inventory of the various cost series discussed above, we find that we have three which are of primary interest in studying trends and making future projections. These are per-barrel historical exploratory cost; per-barrel historical developmental cost, and per-barrel production cost. There is no need to add these three costs together; the total would be meaningless except under very restrictive assumptions. These three costs can be combined only on the basis of detailed estimates as to prospective returns to exploration and to future production patterns from past and present new discoveries, extensions, and revisions.

We also have three series which can be added together to obtain a per-barrel total cost of exploration and development which can be used to estimate total current costs for profit study. These three series are (1) per-barrel exploratory cost for all oil actually produced in the given year; (2) adjusted per-barrel developmental cost for all oil produced in the given year from the extensions of past years, and (3) per-barrel production cost. Here it is the total of the three costs which is of greatest interest; the individual items can be projected, as before, only on the basis of detailed estimates as to future production patterns.

Having distinguished these series according to their use, we return to our earlier question: How could the records kept by the individual pool operators in the manner illustrated in our last numerical example be aggregated to obtain a national figure? Let us take the three "historical" series first.

(1) Historical per-barrel exploration cost: For the year of original discovery this would be the weighted average of the initial estimates of all individual operators. It could be revised only by obtaining information from the individual operators on subsequent extensions and revisions to specifically identified pools, and taking

the weighted average of the currently revised estimates for pools of the original discovery year.

(2) Historical per-barrel developmental cost: This would be the weighted average of the current-year estimates of all individual operators as taken from their own data on costs and extensions.

(3) Per-barrel production cost: This would be the weighted average of the current-year estimates of all individual operators as taken from their own reports.

In each of these cases, the "weighted averages" could be obtained simply by summing all of the costs reported for each category, and then dividing by all the reserves discovered, developed, or produced for the same category. Given sufficiently complete reports from individual pool operators, reasonably standardized as to account classification, there would be no difficulty in making the aggregation.

For the "replacement cost" series the problem would be much the same, as applied to current data:

(1) Per-barrel exploration cost for all oil actually produced in the year: This could be done currently by merely taking the weighted average of all the current-year estimates of all individual operators as submitted in their own reports. This cost would be subject to revision in the light of future revisions of the historical per-barrel exploration cost; but any future revisions could also be obtained from the future corrected reports of the individual operators on a weighted-average basis.

(2) Adjusted per-barrel developmental cost for all oil produced in the given year from extensions of past years: This would be the weighted average of the given-year estimates of all individual operators, as

taken from their own reports. (The weighted average would have to be taken by dividing total allocated development cost for the year's production by the total oil produced from extensions in past years. The numerator would be determined by multiplying the allocated unit cost per barrel by the number of barrels produced from that cost-allocation unit. The weighted average thus obtained for the whole country should then be multiplied by the ratio of given-year production from past extensions, to total given-year production.)

(3) Per-barrel production cost: This would be the weighted average of the given-year estimates of all individual operators as taken from their own records. (This is the same figure as for the "historical" series.)

Clearly such a computation would be a formidable project. Yet something very much like this is nearly a minimal requirement for obtaining any really useful information on trends in oil industry costs and profits. The above process involves many compromises, and it is to be feared that anything more inexact would indeed be a makeshift.

But if it is a question of using a makeshift estimate, or having no estimate at all as a guide, there are two ways of modifying the rigors of the foregoing procedures. First, adjusted per-barrel developmental cost for all oil produced in the given year from extensions of past years could be dealt with by combining it with per-barrel production cost. Under this type of treatment, all development costs would be charged off currently against the production of the given year. This would mean that any important trends in current development cost would be sacrificed, but at least it would not go to the full extent of neglecting per-barrel exploration cost. Two things may be said for this procedure, apart from its simplicity: (1) It does not affect the availability of per-barrel exploration cost. (2) The historical per-barrel developmental cost could still be determined as a national average on a year-by-year basis; this would at least supplement the reduced information with regard to given-year profit considerations. Since the historical per-barrel developmental cost figure is not subject to annual recomputation, we would not lose this series by the recognition of our inability to make the computation each year on an individual pool basis.

The second way of simplifying the calculations is to employ an expedient to minimize the need for recomputation of the historical per-barrel exploratory cost series. This device would be needed, not only to reduce the number of recomputations to be made, but also to allow some projection of the number of barrels of extensions and revisions that can ultimately be expected to result from the discoveries of the initial year. This device, the estimated ratio of initial year new discoveries to ultimate new discoveries, extensions, and revisions, is urgently needed, and it would be desirable to devote considerable effort to the analysis of available data (such as it may be) with a view toward making as accurate as possible an estimate of this ratio. This of course assumes that there is some stability in the size of the ratio. This would seem to be the case on *a priori* grounds, but we cannot say until the available information has been assembled and analyzed.

Let us state the problem and consider the factors which are likely to act as variables in determining the final ratio. Then let us examine the empirical evidence which we must have in order to test any such hypotheses as may be suggested by the suspected relationship of the relevant variables.

The problem is this: given the number of barrels of new discoveries made in a given year, how can we estimate the number of barrels of extensions and revisions which will ultimately be added to these initial-year new discoveries? This is the major question. It would also be desirable to know the probable time-sequence of the addition of these extensions and revisions, e.g., can we assume that typically x per cent of ultimate additions is added in the first year following discovery, y per cent in the second year, and so on?

As to the variables involved, we could draw a distinction between average pool size, technological progress, and the always important factor of pure chance. Average pool size seems to be the most important variable. Assuming that subsequent extensions by development wells are to some extent a matter of chance, the larger the pool that is discovered, the greater the probable total volume of extensions that will be added in later years. Given the usually conservative initial estimates of reserves, then the larger the average pool size, the greater the additions in subsequent years through revisions. Surely this goes without saying, but the important consideration is the hypothesis that larger pools have more-than-proportional potential for subsequent-year reserve additions; naturally the absolute number of added barrels of reserves will be greater for the larger pool, but it seems likely that the ratio of ultimate reserves to new discoveries will be larger for the large pool than the small pool. (As noted before, it could be precisely the reverse; only the empirical data can be decisive here.) So we would expect the following: ultimate reserves are proportional to the size of total new discoveries, but beyond that they are related more directly to the size distribution of pools discovered within the year. If 500 million barrels of new discoveries were made in each of two years, it would be incorrect to apply the same ultimate-reserves ratio to both years if the average size of pools found were only one-half as great in the second year. Technology, as a variable, is related to the problem in two ways: exploration technology, which primarily influences new discoveries but which may also increase extensions and revisions; and secondary recovery technology, which contributes to revisions. Exploration technology is undoubtedly related in some way to the trends in the average size of pools, but this trend is complicated so much by the chance factor that the relationship is not immediately obvious. The net effect of exploration technology is to discover first the larger and more obvious pools capable of discovery by a given level of technology. With technology more or less stationary, exploration is carried toward the intensive margin of ever-diminishing returns in terms of smaller and smaller average pool size. When technology improves, the larger pools capable of discovery by the new method are likely to be among the first found; then the intensive margin is again pursued with decreasing returns in smaller average pool size. Of course, the picture is complicated by the large chance element in exploration, but it does seem that there has been no basic improvement of real importance in exploration technology since the middle 1930's, and this is one of the reasons for the decreasing average size of pool found.

We might hypothesize that the ratio we are looking for will vary with average size of pool, and that, relative to a given level of exploration technology, average size of pool tends to decline over time as diminishing returns set in. The trend in improving secondary recovery techniques acts in the other direction; here there is improvement, but it is likely that the larger pools gain relatively more from these improvements.

Let us now specify the type of empirical information which would be needed to investigate this problem. There is nothing esoteric about the nature of the data involved; only the process of compilation would be arduous, and the amount of historical information which is available would be a matter which might limit the usefulness of the ratios developed. The farther back the information can be obtained, the more conclusive would be the results. What is needed is simply a breakdown of the extensions and revisions (each separately) for each year, by the pool of original discovery, showing the year of discovery of the pool, and the amount of reserves initially estimated as new discoveries for the pool. The basic data could be collected annually from each operator as follows:

Year Found	*Pool Name*	*Original Est. of New Discoveries (Thousands of bbls.)*	*Additions to Reserves in 1960 (Thousands of bbls.)*	
			Extensions	*Revision*
1901	Okla. X	500	50	20
1901	Okla. Y	800	60	10
.	.	.	.	.
.	.	.	.	.
1959	La. Z	300	200	50

The compiling agency would then prepare the following types of analytical summaries:

(a) Cumulative record on individual pool:

Pool	*Year Found*	*Orig Est. of New Discoveries*	*Barrels of Extension Added in Subsequent Years*			
			1st year	*2nd year*	*3rd year*	*. . .nth year*
Okla. X	1901	500	310	130	100	. . .

Columns for revisions and for the total of extensions and revisions should also be provided.

(b) Cumulative record on each discovery year:

Year	*No. Pools Found in Year*	*Avg. Size of Pool (thous. of bbls.)*	*Thousands of Barrels of Extension Added in Later Years*			
			1st year	*2nd year*	*3rd year*	*. . .nth year*
1901	103	800	11,900	9,100	6,700	. . .

Columns for revisions, and for the total of extensions and revisions should also be provided.

The resulting material might well be analyzed with the aid of the following scatter diagrams:

(1) For yearly data, plot the average size of the pool on one axis, versus the time for which the adjusted average size of the pool is measured, with "zero" being the year of original discovery, "one" being one year later, etc. The charts could be drawn up separately for extensions, for revisions, and for both together, and regression lines computed for each. For instance, if the average slopes of the regression lines were roughly parallel, the rate of growth through extensions, revisions, or both (as the case might be) would depend primarily on the initial size of the average pool. If the slopes were not parallel, it could be ascertained whether or not the curves for years of initially larger new discoveries were steeper or more nearly level than those for years with initially smaller new discoveries. Each yearly series would be labelled, and a test could be made to see if the year of discovery had any uniform influence on the shape of the curves.

(2) For pool data, one could plot the adjusted size of pool, individually rather than on the basis of yearly averages of initial sizes. If this should be too much information to present on a single diagram, the data could be presented for groups of pools by size intervals (e.g., initial discoveries from 100 to 200 thousand barrels) and the data averaged to reduce the number of lines to be compared. It would also be useful to plot the pool data by tracing the history of all pools discovered in a given year, and comparing the trends of one year with those of another.

In inspecting the resulting scatter diagrams, the more important things to look for would include: similarities in rates of growth relative to original pool size; whether or not any relationship is present; whether or not the relationship is correlated with year of discovery; the point at which the curves begin to flatten appreciably; how this point is related to the initial size of the pool and to the year of discovery.

One possible way of facilitating this analysis would be to determine by inspection which scatter diagrams seem to show the most promising correlation, and observing the number of years after discovery at which the growth curves began to approach the horizontal. For example, suppose that the individual pool data show the most promise, with a tendency to become horizontal after eight to ten years. One could then, as a first approximation, compute a multiple correlation between the number of barrels of reserves allotted to a pool on various dates with (1) the original size of the pool, (2) the number of years since its discovery, and (3) the year of original discovery. A multiple correlation could then be computed without variable (3) as a rough-and-ready means of determining whether or not (3) added anything to the correlation index. If the data appear to warrant it, more elaborate statistical procedures could then be employed.

It might be found, for example that the estimated size y of a pool x years after its discovery varies primarily with regard to its original size A. The equation for this relationship might be of the form

$$y = A(B)^{Cx}$$

where B and C are constants, C being less than one in value. Such a curve would level off and tend asymptotically to a limit. After ten or so years, for example, 90 per cent or more of the ultimate reserves should have been credited to the typical pool. It is this type of measure for which we are seeking. If ultimate reserves are only a function of the size of gross discoveries (A) in a certain year, then to estimate ultimate reserves (y), we merely solve this equation. If ultimate reserves are a function of the size of the individual pool, then it will be necessary to take into account the size distribution by pools of the new discoveries made in the year under consideration.

At present, all we can do is to look at the only available data which have been published in this field, those of H. J. Struth, whose most comprehensive estimates seem to be those reported in the July 1954 issue of *World Petroleum.* These data are analyzed below:

Year	*Ratio of Original Discoveries plus Ultimate net Credits to Initial Discovery Estimate* (1)	*Column (1) Divided by no. of Yrs. Elapsed since initial Discovery* (2)	*Column (1) Divided by no. of Yrs. Elapsed since Discovery or 8, Whichever Less* (3)	*Average Extensions & Revisions per Pool in Thousands of Barrels* (4)	*"Expansion Power" of Avg. Pool: Contribution of Each Pool to Ratio in Column (1)* (5)
1937	3.00	.18	.38	13,400	.0217
1938	3.88	.26	.49	8,126	.0133
1939	6.67	.44	.83	9,035	.0295
1940	7.86	.56	.98	7,158	.0260
1941	5.19	.40	.65	4,584	.0125
1942	8.20	.68	1.02	4,919	.0200
1943	8.00	.73	1.00	4,575	.0151
1944	6.49	.65	.81	3,984	.0092
1945	8.30	.92	1.04	3,823	.0099
1946	9.79	1.23	1.23	3.727	.0144
1947	6.97	1.00	1.00	3,071	.0089
1948	6.48	1.08	1.08	3.241	.0079
1949	3.28	.66	.66	5,398	.0062
1950	4.21	1.05	1.05	3,039	.0055
1951	3.36	1.12	1.12	2,067	.0049
1952	2.31	1.16	1.16	2,512	.0049
1953	1.43	1.43	1.43	2,681	.0044

Sources: Column (1) H. J. Struth, *World Petroleum,* July 1954, p. 62. Column (4) Total number of pools discovered per year estimated by total number of successful oil-finding exploratory wells. Data from *Bulletin of American Association of Petroleum Geologists,* June issues, 1951-54.

Note: No underestimation of the data for the most recent years is likely to exist in columns (4) and (5)—the bias may be toward overestimation since new discoveries for 1947-1953 have been multiplied by 8.72, a presumably liberal estimate for all future extension and revisions. (See page 78).

This is about as far as one can go at present in estimating the ratio of new discoveries to ultimate reserves found in a given year.

Struth's data are given in column (1). In column (2), these estimates have been divided by the number of years elapsed between the year of the original discovery and 1953, the year for which column (1) estimates were prepared. In column (3), these estimates have been divided by the number of years elapsed since the original discovery, providing that it does not exceed eight years. The first computation assumes that all fields are constantly being credited with some extensions and revisions, and therefore represents an effort to derive an average ratio, which we might call z. The original reserve estimate can then be multiplied by z so that this product can in turn be multiplied by the number of years elapsed since the original discovery, to obtain some estimate of the amount of reserves discovered in the original year, or directly attributable to the new pools and fields found in the original year. In other words, we have the expression:

$$D_o = (z \cdot d_o)\,(i - o)$$

where D_o = the estimate of total reserves discovered in year o as estimated in the year i

z = average increase factor per year

d_o = initial reserve discoveries

In this expression, the estimate of total reserves discovered in year o is equal to the initial estimate of reserves discovered multiplied by the average increase factor per year, and this product is then multiplied by the number of years between the initial discovery year o and the year in which the estimate is made, i.

In the second computation, D_o is considered to increase at a constant rate z per year until eight years have elapsed from the year of original discovery, at which time further extensions and revisions are assumed to cease. This is the cut-off point which was suggested by an appraisal of the available data.

We can see from the table that the first assumption yields an approximately constant value for z for the last eight years, but that it falls noticeably before that time. The assumption that eight years will exhaust the vast majority of extensions and revisions yields a value of z that decreases more slowly, from an average of 1.09 for 1946-1953 to .90 for 1939-1945, and then falls off to .44 for 1937-38. With the exception of 1949, the value of z for the last eight years is notably stable, and if we attempt to explain the apparent decrease in the average yearly increment to new discoveries by virtue of extensions and revisions, two suggestions come to mind: (1) perhaps there is a qualitative difference in the basic data available to Struth before 1946, separate American Petroleum Institute estimates of extensions and of revisions not being published, apparently, before 1946; (2) in the years before 1939 some very large fields were found, and wildcat wells on the whole seem to have been more successful than they have been since the war, particularly with respect to the average size of field discovered, so that there may have been a readiness to engage in exploratory drilling instead of the development of existing fields in order to add to reserves. Today, faced with smaller returns to exploratory drilling, the number and average depth of development wells has increased considerably as the result of an attempt to maintain production and reserves in the face of a falling discovery rate, so that extensions and revisions to recently discovered fields may perhaps be added at a more rapid rate than in the pre-war period because of more intensive follow-up development in a short period of time. But neither of these considerations can be said to offer anything more than suggestions toward explaining the inconstancy of z, so that it is probably better not to place too much confidence in the apparent stability of z during 1946-1953.

As an example of the possible use of the z factor, it may be instructive to make an estimate of the average size of oil pools discovered from 1937 through 1953. The number of pools discovered was estimated from the number of successful exploratory wells in each year; and the total number of barrels of new discoveries, extensions, and revisions credited to the discovery year by 1953 was divided by this estimate. This procedure was followed for the years prior to 1947-1953; subsequent-year initial new discovery estimates were multiplied by a factor of 8.72 (the average value of z for the period 1946-53); this value was then multiplied by the period of time during which additions to reserves were considered likely to be made, i.e., 8 (years) times 1.09 per year. The results show that even with this liberal upward adjustment, *all* the years before 1947 exceed the largest of the post-1947 years, with the exception of 1949.

(4) *The allocation of joint costs between liquid hydrocarbons and natural gas.* Now we arrive at what is probably the most difficult problem of all: the allocation of joint costs among discoveries of crude oil, natural gas liquids, and natural gas. Up to this point, we have been dealing with cost allocation as if the product discovered were simply crude oil. The reason for this oversimplification is obvious enough: it is conceptually impossible to allocate joint costs on a basis which is not arbitrary. However, as the proportion of natural gas found to crude oil discovered continues to increase, and as governmental regulatory bodies become more concerned with natural gas "costs," there is an apparent demand for some device by which total costs may be allocated—arbi-

trarily if necessary—to the types of resources discovered by exploratory efforts. Most industry studies have ignored natural gas entirely—as we have been doing. But this neglect is certainly in itself an arbitrary decision. The only way to escape this arbitrariness would be to content one's self with the statement that $\$x$ of outlay in year y resulted in the discovery of a barrels of crude oil, b barrels of natural gas liquids, and c cubic feet of natural gas, with no attempt made to allocate costs among heterogeneous products.

For that matter, crude oil itself is not a homogeneous product, and for more than ten years, many students of the problem have been combining crude oil and naural gas liquids (condensate, natural gasoline, and liquefied petroleum gases) on a volumetric basis, barrel for barrel, with various corrections for energy value equivalent or market price. Very few published treatments, however, have gone to the extent of combining crude oil, natural gas liquids, and natural gas on any common basis. This is no doubt to their credit, if they saw the choice in terms of an "either/or" proposition, i.e., *either* to measure productive results in units of crude oil alone, *or* to measure them in terms of combined oil-and-gas units. However, it is probably true today that so high a proportion of current returns to exploration is being found in the form of natural gas, that a "both/and" approach is necessary, i.e., *both* measure productive results in terms of crude oil alone, *and* also supplement this information with a measurement in terms of combined oil-and-gas units. Here again, the two sets of data would have to be studied in relation to one another.

Assuming that it is necessary to develop some type of supplementary measure to link oil and gas discoveries together, how should it be done? There are really only two methods which have been devised for the allocation of true joint costs.

One of these methods is called the "selling price" or "expected revenue" method, and is completely misleading if used as the basis for managerial decisions. To apply this method, you reason as follows: if oil sells for $\$x$ per barrel, and gas sells for $\$y$ per thousand cubic feet, and if a cost outlay of $\$z$ has discovered 1,000 barrels of oil and 500,000 cubic feet of gas, then one allocates the total cost between oil and gas in the ratio of the expected revenue to be derived from each. The total cost of discovering oil would then be $\frac{\$x\,(1{,}000)}{\$y\,(500) + \$x\,(1{,}000)} \cdot z$; the cost of discovering gas would be the remainder, and the unit cost of discovering each could then be computed. But in application this would be folly. There is no reason whatsoever for allocating costs in proportion to revenues, and, therefore, making unit costs proportional to prices. Costs and prices are determined by largely independent factors, especially in the case of crude oil and natural gas, and the application could lead to serious errors. Suppose that joint costs are allocated by this formula. Then suppose that the market price of oil increases. This automatically brings with it an increase in the (allocated) cost of finding oil, and a decrease in the cost of finding gas. That the result is ridiculous is obvious on the face of it: why should the cost of finding gas fall because the market price of crude oil has risen? And it would be even worse if petroleum industry management were then to increase the intensity of gas-finding effort because the costs of finding gas had fallen!

If it is mandatory that some allocation method be used, the method of allocating costs on the basis of some common physical characteristic of the joint products wins by default. Oil and gas are relatively fortunate here, in that both can be compared on the basis of a dimension which is the chief reason for the demand for each. If gold and lead were jointly produced from a certain mine, joint costs could be allocated on the basis of weight, which is a homogeneous dimension—but this would be a poor choice because weight is one of the least important of the common dimensions which might make one of these metals to some extent a substitute for the other in terms of demand. But for oil and gas, there is always the common denominator of the energy equivalent, generally stated in terms of potential heat energy in British Thermal Units, or B.T.U.'s.[32]

There is something to be said for comparing both oil and gas in terms of B.T.U.'s. Two energy sources are here being treated as identical; fortunately, they are somewhat similar. If it were true that a B.T.U. of crude oil were perfectly substitutable in the market for a B.T.U. of natural gas, the comparison would be perfectly justified; indeed there would then be no need for joint costing, because the products would be absolutely identical in the market. Unfortunately, they are not identical in the market, but the comparison is somewhat reasonable because in a substantial part of the crude oil market, natural gas is directly competitive with crude oil products on a B.T.U. basis. About 35 to 40 per cent of the products refined from crude oil has consisted, in recent years, of distillate and residual fuel oils, which are sold in a market conscious of the B.T.U. content of crude oil relative to that of natural gas. Furthermore, it is quite generally believed by geologists that the over-all incidence of total B.T.U.'s in the form of oil, and total B.T.U.'s in the form of gas is approximately equal in the earth's sedimentary basins. Therefore, in the long run, the chance of finding a B.T.U. of gas would be just about the same, per dollar of discovery expenditure, as the chance of finding a B.T.U. of oil. This is, however, a very long-run consideration.

There are several disadvantages to using the energy factor for cost allocation. First, there is the fact that 60 to 65 per cent of the end uses of crude oil products are not directly competitive with natural gas, because B.T.U.'s are not the only important characteristic. Convenience, for example, is often of crucial significance. Who would elect to undertake residential space heating with crude oil if it were only slightly cheaper than gas on a B.T.U. basis? Second, the use of the energy factor ignores the conversion cost of transforming one resource into another. Natural gas could be processed into the equivalent of crude oil, but the expense involved would have to be taken into account. Yet the comparisons made in energy terms alone seem to assume that this can be neglected. Finally, there is the difficulty that the gross total B.T.U. figures will not disclose the ratio of oil to gas. Suppose you have discovered x billion B.T.U.'s for an outlay of y dollars. Then the unit cost allocation is the same, regardless of the ratio of oil to gas. But clearly the implications for total profits will depend upon this ratio, even if formally determined unit costs would not.

If joint costs must be allocated, it is much more desirable to use the B.T.U. basis than to use the sale price basis. It is obvious that once it is decided to use B.T.U.'s to compare crude oil and natural gas on an energy basis, it is then a matter of indifference as to the units used to compute costs. It would probably be most logical to express costs in cents per B.T.U., or per million B.T.U.'s. But those who are accustomed to thinking in terms of barrels of crude oil, or millions of cubic feet of natural gas, may feel uncomfortable and perhaps even somewhat disoriented because the energy units seem somehow "abstract." As a basis for the empirical analysis in Section III, the following table shows all discoveries of crude oil, natural gas, and natural gas liquids for the period 1947-57 in terms of their equivalent number of barrels of crude oil.

	Crude Oil		*Natural Gas*		*Natural Gas Liqd.*		*Total (Millions of bbls.)*	
Year	*New Disc.*	*Total**	*New Disc.*	*Total**	*New Disc.*	*Total**	*New Disc.*	*Total**
1947	445	2464	632	2054	59	252	1136	4770
1948	396	3795	765	2585	65	471	1226	6850
1949	890	3188	855	2364	93	387	1837	5938
1950	565	2563	533	2243	58	766	1156	5571
1951	389	4414	563	3000	75	724	1027	8137
1952	496	2749	1003	2696	82	557	1581	6002
1953	592	3296	1312	3887	96	744	2000	7927
1954	586	2873	921	1796	86	107	1593	4776
1955	477	2871	1060	4081	67	515	1604	7467
1956	467	2974	1044	4605	94	810	1605	8389
1957	416	2425	1660	3720	129	138	2145	6145

Source: American Petroleum Institute and American Gas Association, annual reports on oil and gas reserves.

* Denotes total of new discoveries, extensions, and revisions.

This table shows that the inclusion of natural gas in the total energy discoveries more than doubles the volume of total discoveries in the years 1955-57, and approximately doubles it in 1952-54. In 1947-51, natural gas discoveries were about 80 per cent as large as total liquid hydrocarbon discoveries. Clearly the inclusion of natural gas changes the complexion of the discoveries picture significantly. It is unfortunate that comparable data for natural gas discoveries are not available prior to 1947.

III. A SURVEY OF CERTAIN APPARENT TRENDS IN THE COST OF FINDING OIL AND GAS RESERVES IN THE UNITED STATES

THIS section is a survey of some of the most pertinent available data on trends in the cost of finding reserves of crude oil, natural gas liquids, and natural gas in the United States. Unfortunately, the available data for such a study are far from complete, and much of what would be most useful for our purposes is entirely lacking. As a result, indirect and approximate measures have been resorted to almost exclusively. The most desirable approach would consist of a definitive analysis of all the relevant data; but in view of the absence of most of these data, we are forced to rely upon such data as are available. In certain instances, the reliability of the data used could not be satisfactorily ascertained. In such instances it was judged preferable to have recourse to an available approximation rather than remain entirely in ignorance on the matter in question.

The cost of finding oil and gas reserves is defined as the average cost, in dollar terms, per unit of reserves discovered in a given period of time. This definition is simple enough, but before we can determine the magnitude of this ratio we must resolve the following problems: (1) Where do you get reliable data on total dollar outlays on finding programs? (2) Have the various elements of cost been properly defined? (3) What is the physical volume of reserves discovered by the outlays of a given period? (4) How should we allocate the joint costs of finding crude oil, natural gas liquids, and natural gas to the individual products? (5) How should we eliminate the effect of price changes on the dollar costs of various years in order to make them comparable? The resolution of all of these problems would be essential to a comprehensive study of finding costs. For present purposes, however, we can do a little more than to suggest an approach to the solution of each of these problems.

(1) The collection of reliable information as to total dollar outlays on finding programs would require industry-wide reporting of such outlays or the use of a carefully designed sample. To date, there has been no successful compilation of total dollar outlays on an industry-wide basis and the scattered reports which have been collected certainly do not satisfy the minimum requirements of good sampling design. In the absence of reliable data on dollar outlays, it is necessary to use some single dimension of cost, such as total wells drilled, or total footage drilled, to construct an index of the real cost per unit of discoveries. This is the approach taken in the first section of this paper.

(2) A necessary prerequisite to the collection of the reliable cost data is the proper definition of various cost elements. For example, there is the problem of distinguishing between those outlays that are for exploration purposes, and those that are for field development. It seems that it would be most appropriate to include in finding (or exploration) costs, all the costs of lease acquisition, all geological and geophysical expenditures, the drilling costs of all exploratory wells, and the costs of completing the successful exploratory wells, through the installation of the Christmas tree. Drilling costs for such wells would then be defined in a manner identical with that used by the Joint Association Survey.[33]

(3) The determination of the physical volume of reserves discovered in a given period is a problem of the first magnitude. All that need be said here is that it should not be a conventionally conservative estimate, but should represent the

best-informed estimate of probable ultimate recovery from the entire reservoir discovered by the exploratory well. Naturally the future will prove that the estimate has been only approximate; accordingly, the estimate, and the relevant unit cost figure, should be revised from time to time in the light of the future production history of the field. Still, this does not make it any less important to obtain the most accurate initial-year estimate that can be devised.

(4) As was mentioned in Section II, the joint cost problem is ultimately incapable of logical resolution. Any allocation of discovery costs between jointly discovered products must be inherently arbitrary. Two ways of handling the problem seem acceptable. First, one may allocate all costs to the physical units of crude oil or total liquid hydrocarbons discovered, ignoring the fact that some gas has also been discovered. This is perhaps the most common treatment, but it is arbitrary insofar as it overlooks entirely the fact that some natural gas has been discovered. Second, one may use the B.T.U. equivalent of natural gas to convert natural gas in cubic feet into its equivalent in barrels of crude oil; or all products may be converted into their B.T.U. equivalents and a single cost figure per B.T.U. may be derived. This is arbitrary in that it treats all these heterogeneous hydrocarbons as being comparable in terms of their potential energy equivalent; so comparable, it is assumed, that they are considered to be identical. But other characteristics of these products, in addition to their potential heat energy content, are equally important in the market. The B.T.U. equivalent is therefore an oversimplified way of dealing with the problem. (For details, the reader is referred to the discussion at the end of Section II.) Nevertheless, if joint costs must be allocated, there is probably no better basis for the allocation of joint

discovery costs than the B.T.U. equivalent, despite its inadequacies.

(5) The adjustment of dollar costs to allow for changing purchasing power equivalents at various price levels is another extremely complex problem. A rough-and-ready solution can always be had by resort to an index of the general price level. For more demanding uses, it might be preferable to devise an index of the expected level of prices that confront the industry. The success which one has in solving this problem will depend upon the availability of statistical data, and upon one's ingenuity and resourcefulness in making the most expedient price index adjustments.

These are the problems which confront any study of the trends in the cost of finding oil and gas reserves. In view of the limitations of the available data, the present study has made the following concessions to necessity:

(1) Virtually all of the exploration outlay data considered herein consists of real-cost data. Specifically, the volume of reserves found in different discovery categories is measured in terms of barrels of discoveries per exploratory well, per dry hole, per foot drilled, and the like. No continuous year-by-year series of acceptable quality on total money outlays is available; hence real cost data constitute the bulk of the statistical evidence for establishing trends.

(2) The outlays have been defined, by and large, in real terms. The published data on wells drilled and footage drilled are investigated in terms of as complete a breakdown by drilling categories as can be obtained from the available data. When recourse is occasionally had to money outlay statistics, we are working with data the nature of which is neither well defined nor well described by its compilers. Consequently, less confidence can be placed in the meaning of the results which are obtained from the use of these data.

(3) On the basis of the data currently available, it does not seem to be of any value to try to estimate the ultimate reserves discovered in a given year by crediting subsequent extensions and revisions back to the year of initial discovery. It is to be hoped that adequate data will someday be developed so as to permit

this procedure, but that day has not yet arrived. Instead, this study concentrates on the composition of current additions to total discoveries, using new discoveries alone for some purposes, new discoveries plus extensions for others, and the total of new discoveries, extensions, and revisions for still other purposes. In general, it is considered preferable to measure current discoveries in terms of the statistics for current additions to total cumulative discoveries, rather than to attempt to allocate extensions and revisions backwards, and thereby to introduce at best some distortion between the amounts allocated to earlier and later years.

(4) By and large, the joint cost problem is dealt with by means of the first alternative discussed above: that of allocating all relevant costs to the crude oil component of discoveries, and ignoring other liquid hydrocarbons and natural gas. However, information is given on the recent ratios of discovery of crude oil to total liquid hydrocarbons and natural gas, and in a few instances real costs are computed both on the basis of crude oil alone, and of the crude oil equivalent of all liquid hydrocarbons and natural gas combined.

(5) Since most of the cost indexes employed are real cost indexes, the problem of obtaining comparability between dollar figures seldom arises. This is not to say that real cost indexes are always comparable. A good example is the case of the exploratory well. The average exploratory well seems to become increasingly deeper over time, so that it is necessary to supplement data on discoveries per exploratory well with those on discoveries per exploratory foot. Even the exploratory foot is not a homogeneous unit over time, since the real cost of drilling, at the same depth level, tends to decrease as technological progress cuts unit drilling costs. On the other hand, a foot drilled at five thousand feet is not the same as a foot drilled at fifteen thousand feet; given the same level of technology, costs per foot increase sharply with increasing depth of drilling. Here, dollar costs would have been an invaluable supplement to real cost figures, had they been available. In those few instances where money cost figures have been employed, a simple and approximate price level adjustment has been made by means of the index of wholesale prices.

Let us begin the survey of the trends in the real cost of finding reserves by examining one measure of the real cost of exploration which can be approximated for an interval of some fifty years. Chart I shows the average number of barrels of crude oil discovered per new well completion, as related to the cumulative total of well completions. Following the example of P. R. Schultz,[34] the data have been subjected to a three-year moving average, merely to remove the extremes of year-to-year random fluctuations. Even so, it can be seen that until 1947, fluctuations in the smoothed data were quite pronounced. Despite the marked fluctuation, a general pattern of first increasing, and then declining, average discoveries per new well completion is apparent. A parabolic curve has been fitted to these data, with the following equation resulting:

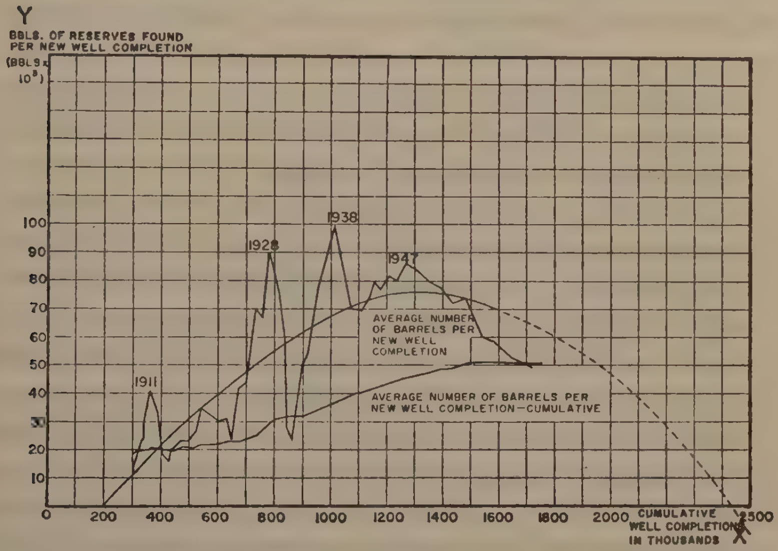

Chart I: Barrels of Crude Oil Reserves Discovered per New Well Completion, vs. Cumulative Well Completions, 1907-1958. (Three-year moving averages)

$$Y' = -36.745 + .173775X - .0000688792X^2$$

where Y' is thousands of barrels of reserves of crude oil discovered per new well completion

X is cumulative new well completions, in thousands.

For this computation, the index of determination is .6406 indicating that 64.06 per cent of the total variation in the discoveries made by new well completions is associated with the accompanying variation in cumulative well completions. The index of correlation is .8003. The standard error of estimate is 14.78, indicating that, for the period covered, the probability is .6827 that the actual observed value of discoveries per new well completion will not differ from the value computed from the equation by more than 14,780 barrels, either above or below the computed value. Furthermore, the probability is .9546 that the actual value will not deviate above or below the computed value by more than twice the standard error of estimate, or 29,560 barrels; and the probability is .9973 that the actual value will not deviate above or below the computed value by more than three times the standard error of estimate, or 44,340 barrels. The correlation coefficient is significant at the .001 level, indicating that there is less than one chance in a thousand that the observed correlation is due purely to chance. (It is recognized, however, that conventional tests of significance are not necessarily applicable to time series data.)

This chart shows decreasing returns to drilling, and therefore increasing costs per unit of crude oil discovered. What is the meaning of these historical data and the predicted parabolic decline curve for the future? Our view of the matter may be explained along the following lines. The supply of hydrocarbon reserves to be exploited in the form of liquid hydrocarbons and natural gas is ultimately fixed in amount. The pattern of exploitation of these reserves will eventually lead to complete depletion. If the firms in the petroleum industry possessed complete advance knowledge of all the characteristics of their fixed stock of irreplaceable resources, they would select the optimum technological method for exploiting them, i.e., that method which would maximize long run profits. In the course of the application of this optimal method, a production pattern of the diminishing returns variety would be achieved. Under these circumstances, with perfect knowledge of the location of the most profitable deposits, the firms would first apply their variable resources (drilling rigs, crews, etc.) to the most productive portions of their fixed supply of raw materials (the oil fields themselves). At any time there would be both an intensive margin in the exploitation of the most prolific pools, and an extensive margin in the initial tapping of less productive pools. The intensive margin can be thought of in terms of the appropriate spacing of wells over large pools; the extensive margin can be visualized in terms of the drilling of outpost wells or new pool wildcats where smaller pools can profitably be tapped. Let us look upon the exploratory well as making a contribution to cumulative total discoveries of crude oil. The amount of discoveries which the exploratory well brings in is its addition, at its intensive or extensive margin, to total cumulative discoveries. We can look upon the volume of discoveries made by an individual well as constituting its *marginal productivity,* to use the appropriate term in economic theory. The marginal productivity of a well is the total volume of discoveries which it contributes to total cumulative discoveries. Where a process is characterized by diminishing returns, the marginal productivity of the variable factor or factors (here conceived of as well completions) typically follows a pattern where there is an initial stage of increasing returns, followed by a point where a maximum is reached, after which diminishing returns begin to set in, causing the marginal productivity of the variable factor or factors to decline steadily until the zero level of productivity may be reached. If we assumed that all firms in the petroleum industry had perfect knowledge of the extent of their oil deposits, in advance of any drilling, we might expect that the discoveries made by successive well completions would follow this classical pattern of diminishing returns.

In the case of imperfect knowledge of the stock of reserves, the marginal productivity of a well, in terms of proving reserves, will depend at any time on the state of exploration technology in the industry. With a given state of technological knowledge, the industry will exploit the opportunities made known to it in such a way that the better opportunities are taken up first, and the inferior ones left until later, so that diminishing returns can be expected within the horizon of the prevailing level of technology. At a given state of knowledge, only so many possibilities will be suspected; these will be exploited in their order of potential promise. When improvements in technology occur, the horizon shifts, and diminishing returns will begin to operate again, but within the framework of a larger realm of exploration possibilities. We should then expect to see the marginal productivity of a well slowly decrease until an innovation in exploration caused an upward shift in the entire marginal productivity horizon, from which point the marginal productivity would once again begin to decline. If knowledge of this exploration technology is not available to all the operators in the industry, because of costs, or because a good number of the operators prefer to drill on "hunches," there will be erratic variations in the marginal productivity of these wells. Beyond this, there will also be random erratic fluctuations in marginal productivity arising not only from the refusal or inability to employ the best available technology, but also from the residual fortuitous element present in even the best techniques of exploration so far devised. Until the technology of exploration is substantially perfected, the chance element in exploration can never be overlooked, and at present with seven out of eight new field wildcat wells failing to produce, the chance element is clearly very important.

Let us interpret Chart I in the light of these considerations. We see that we have three major peaks in average discoveries per well, coming about in 1911, 1928, and 1938. A good case could be made for the hypothesis that each of these peak periods (recognizing of course the effects of smoothing through three-year moving averages) represented the coming to maturity of a certain technique or group of techniques for exploration purposes. This is simply the reflection of the fact that certain techniques are much more successful than others in locating certain types of formations and hence certain types of fields. New techniques have relatively soon found the larger and more obvious new fields for the discovery of which they were best suited, and then they have been used with less and less success, and finally discarded. One authority writes: "One of the most remarkable features . . . is the fact that each method of oil-finding had a relatively short activity span. Surface geology, which hit its stride in 1912, was nearly finished by 1924. The easily found structures in the Rocky Mountain states and in part of California were tested in rapid succession. The somewhat more difficult structures in the mid-continent were found in the later years. The torsion balance found a great many salt domes between 1922 and 1932. The refraction method of seismic surveying, also ideally suited for detecting salt domes, reached a peak in 1937. The reflection method, off to a slow start, accomplished wonders between the years 1929-48, when it also reached a peak. The gravimeter which supplanted the torsion balance reached its peak in 1945."[35] From this, it would seem that shifts in technology do not achieve their maximum intensity of use as soon as they are introduced, but require a shorter or longer period of time to gain sufficiently wide usage to reveal the full extent of their impact on the success rate of exploration. We might interpret the data of Chart I in this manner: there have been three "eras" in exploration technology since about 1900, and each hit its peak of discoveries per well and was followed by a decline until a new era of exploration technology was made possible. The first era might be characterized as that of *surface geology*. It began about 1901, and VerWeibe indicates that its discoveries hit their peak at about 1912, which would agree with the 1911 peak of our own chart. By 1924, discoveries attributable to surface geology alone had dwindled to insignificance. The second era might be termed that of *extensive geophysical methods*. The introduction of these techniques can be dated at about 1920, with the initial small-scale use of the magnetometer and the torsion balance being supplemented by the introduction, also initially on a small scale, of subsurface logging methods, electric logging, and the refraction seismograph in the early 1920's. The initial methods were extensive in scope, consisting primarily of relatively lower-cost reconnaissance methods of torsion balance and magnetometer prospecting, which began to take hold about 1924. The peak of the discovery rate with these extensive geophysical means of exploration was perhaps reached about 1928, as indicated on our first chart. Nevertheless, these extensive survey methods continued to find wider and wider use until about 1932, although after 1928 the effectiveness of such methods fell off greatly. The third era is rather difficult to date as to its beginning. The sharp decline in discoveries in 1930-31 is due more to the effects of the depression and the discovery of the giant East Texas field upon drilling incentives than to the unmitigated effect of diminishing returns to further exploratory efforts, although there should no doubt have been a slight downward trend even in the absence of these two occurrences. We might take 1930 or 1932 as the beginning of the third era, that of *intensive geophysical methods.* The peak of average discoveries per well by this method was reached in the years 1937-39, and ever since that time the average returns to these intensive geophysical methods has been declining. One of the chief reasons, then, for the steady increase in finding costs is the fact that the industry is engaged in a more and more intense exploitation of essentially the same drilling opportunities as are implicit in the same general horizon of exploration technology that has prevailed since the early 1930's. A revolution in exploration techniques, such as that which might be supplied by the discovery of an infallible method for the direct detection of petroleum deposits in the ground, would be the most effective means of lowering finding costs. Such a basic change in technological horizons has seemingly not come about since approximately 1930-32, even if many improvements in detail have been achieved by way of the development of intensive geophysical methods of exploration since the early 1930's.

The third era took six to eight years to build up to its peak of discovery. This might easily be explained by the reluctance of firms to use the higher-cost intensive methods of exploration before the relatively lower-cost extensive methods had proved themselves outdated. The third era has seen the increasingly widespread use of costly, intensive methods of exploration, chiefly the reflection and refraction seismograph. As VerWeibe indicated, the refraction seismograph reached its peak of success in 1937; the refraction seismograph reached a lower peak in 1948, and the newer exploration tool, the gravimeter which replaced the torsion balance, reached its peak of discovery in 1945. We may feel safe in assuming that unless very important changes in exploration technology take place in the near future, the declining curve of Chart I deserves some attention in regard to the probable significance of extrapolation to obtain future trends in discoveries per new well completion.

The data of Chart I do not suggest that these three eras of exploration technology were regular in their cycles of first increasing and then decreasing discoveries per well. Information on the first half of the first era is not available; the second era shows extreme fluctuations around its 1928 peak; and the third era shows a secondary peak in 1947. By way of explanation it may be said that before about 1930, the use of professional geological and geophysical services to guide drilling programs was much less widespread than in the decades thereafter, and the earlier reliance on "hunches" and "creekology" (the inferring of faults from the course of creekbeds) certainly tended to increase the purely random fluctuation present at all times in the series. The depression of 1929 and the discovery of the East Texas field were largely responsible for the decline in discoveries in 1930-32, and the fluctuations from 1938 to 1947 may to some extent be explained by the effect of the second world war emergency on drilling programs, although just how much of the fluctuation is to be attributed to wartime dislocations is not certain. It seems quite likely, however, that the steady decline after 1947 is highly significant. The last ten or eleven years have seen the most intensive exploration program ever carried out in the United States, with systematic and efficient use being made of all the resources available to the industry, at least through the year 1956. The decline is therefore capable of interpretation in this light: with a systematic exploitation of all available opportunities in the order of their seeming promise, the phenomenon of diminishing returns is making itself felt with unmistakable clarity. That the returns to exploratory activity have been declining over time is simply evidence that the companies have been efficient in exploiting the most promising opportunities first of all, and then in having recourse to the successively less promising ones.

Can any information regarding the future be obtained from Chart I? Before giving a general answer, we must point out that the information employed in drawing up Chart I is not the most relevant to the problem at hand, nor is the fitting of a single composite curve to the total body of the historical data an ideal solution to the statistical problem.

Let us consider the second point first. If we were *certain* that there had been three eras in exploration activity, it would have been expedient to compute separate growth and decline curves for each of the three exploratory eras, using curves of parabolic or other similar forms. This was not done because of the impossibility of defining the beginning and end of each era. Instead, a composite curve was fitted, which would seem to result in the making of a relatively optimistic estimate of future discoveries per well completion. This can be seen from the circumstance that discoveries since 1947 have declined more rapidly than would be estimated by projecting the parabolic decline curve.

Second, the information presented gives us a measure of the average discoveries of crude oil, in terms of the current addition to total cumulative discoveries, per new well completion. This means that exploratory and developmental wells are both included in the denominator of our average figure, although it would be much more to the point to measure the discoveries per well only in terms of exploratory wells. This was not done because we were interested in drawing up, at the outset, the best available approximation of the entire historical trend of this index of the real cost of crude oil exploration since about 1900, and for this purpose we had to make use of the longer series on total well completions, rather than the relatively shorter series on total exploratory wells. (Discoveries per exploratory well will be considered below.)

Returning to the parabolic equation for predicting discoveries of crude oil per new well completion in the future, for what it may be worth, we find that we can make several definite "predictions" by way of simple extrapolation alone. These extrapolations are purely formal consequences of the nature of our estimating equation. The equation itself shows the marginal productivity of a single well completion at any level of cumulative well completions. We can integrate the equation for the marginal productivity of individual wells and thereby arrive at the total ultimate figure for discoveries from all wells that can ever be drilled productively. Our discovery curve eventually reaches zero; at that point, diminishing returns have reached their climax, and no further discoveries remain to be made. We can integrate the equation for discoveries per well and evaluate the integral between zero cumulative wells (the beginning of drilling) and the point at which the productivity of an additional well reaches zero, where no more reserves are to be found. Assuming that the arbitrary constant of integration is zero, that is, there are no discoveries made before any wells are drilled, we have:

$$\int Y'\,dX = -\,36.745X + .086888X^2 - .0000229597X^3$$

when $Y' = 0$, $.173775X - .0000688792X^2 = 36.745$; $X = 2289.5$; $\int Y'dX = 105780.5$

when $dY'/dX = 0$, $.173775 = .000137758X$; $X = 1261.5$; $Y' = 72.859$

These computations imply certain things. For one thing, the marginal productivity, or volume of discoveries, of a well completion will reach zero when 2,289,500 wells have been drilled, and ultimate reserves will amount to 105,780,500,000 barrels of crude oil. At the rate of 50,000 wells per year, the limit of discovery would be reached some time in 1969. The peak of the equation was reached in late 1947, when the 1,261,500th well was drilled, its theoretical discovery level being 72,859 barrels of crude oil. Turning to Table II, we see that the actual data estimate of marginal productivity was 60,006 barrels per well completion for the average of the three-year period 1952-54 inclusive; judging from our parabolic equation, the median well drilled during this period would have been about the 1,550,000th well, which should have had a theoretical discovery level of 67,124 barrels. For the typical (median) well of 1952-54, its 60,006 barrels of reserves would have been worth only about $60,000 in place at the time of discovery, given the prevailing price level of that time (one dollar per barrel) for proved reserves in the ground. This is only 20 per cent above the cost of drilling alone: $50,200 for the average well drilled in 1953, as reported by the Joint Association Survey.[36]

Chart II presents a somewhat different way of measuring the same general trend. Here the trend in the number of barrels of crude oil discovered per dry hole is computed for the period 1907-58. Dry holes have been used as a method of estimating the number of exploratory wells actually drilled each year. This is an approximate measure,

TABLE II

BARRELS OF CRUDE OIL RESERVES DISCOVERED PER NEW WELL COMPLETION vs. CUMULATIVE WELL COMPLETIONS, 1857–1900, 1901–58

Year	Wells Drilled (Thou.)	Bbls. of Reserves of Crude Oil Found (Millions)	Avg. Disc. Per Well (Thou. bbls.)	Cumulative Total Wells Drilled (Thou.)	Cumulative Res. Added (Million bbls.)	Avg. Disc. Per Well-Cumulative (Thou. bbls.)	3-yr. Mov. Avg. of Avg. Disc. per Well (Thou. bbls.)	3-yr. Mov. Avg. of Avg. Disc. per Well, Cum. (Thou. bbls.)
1857–1900	174	3,904	22.5	174.0	3,904	22.5		
1901–1905	88	1,410	16.0	261.3	5,314	20.3		
1906	19.1	126	6.6	280.4	5,440	19.4		
1907	19.9	266	13.3	300.3	5,706	19.0	12.2	19.0
1908	16.9	279	16.5	317.2	5,985	18.9	16.9	19.0
1909	18.3	383	20.9	335.5	6,368	19.0	23.9	19.2
1910	14.9	510	34.2	350.4	6,878	19.6	35.8	19.8
1911	13.8	720	52.2	364.2	7,598	20.9	40.8	20.7
1912	17.2	623	36.2	381.4	8,221	21.6	34.0	21.2
1913	25.6	348	13.6	407.0	8,569	21.1	19.0	21.0
1914	23.1	166	7.2	430.1	8,735	20.3	15.9	20.6
1915	14.2	382	26.9	444.3	9,117	20.5	21.0	20.6
1916	24.6	701	28.5	468.9	9,818	20.9	23.4	20.7
1917	23.4	335	14.3	492.3	10,153	20.6	22.9	20.8
1918	25.8	656	25.4	518.1	10,809	20.9	23.4	20.9
1919	29.3	878	30.0	547.4	11,687	21.4	27.9	21.3
1920	34.0	943	27.7	581.4	12,630	21.7	35.6	21.9
1921	22.0	1,072	48.7	603.4	13,702	22.8	30.4	22.3
1922	24.9	358	14.4	628.3	14,060	22.4	31.2	22.6
1923	24.4	732	30.0	652.7	14,792	22.7	24.0	22.6
1924	22.5	614	27.3	675.2	15,406	22.8	41.5	23.9
1925	26.4	1,764	66.9	701.6	17,170	24.5	43.6	24.1
1926	29.5	1,071	36.3	731.1	18,241	25.0	70.5	25.7
1927	24.1	2,601	107.9	755.2	20,843	27.6	67.0	27.0
1928	24.8	1,401	56.6	780.0	22,244	28.5	90.1	29.2
1929	30.4	3,207	105.6	810.4	24,541	31.4	72.4	30.7
1930	23.7	1,298	54.7	834.1	26,749	32.1	60.0	31.8
1931	13.0	251	19.3	847.1	27,000	31.9	26.7	31.8
1932	15.8	86	5.4	862.9	27,086	31.4	23.3	31.6
1933	13.5	606	44.9	876.4	27,691	31.6	34.1	31.7
1934	21.1	1,085	51.4	897.5	28,775	32.1	48.6	32.1
1935	24.6	1,220	49.6	922.1	29,995	32.5	53.8	32.7
1936	29.0	1,763	60.8	951.1	31,758	33.4	71.8	34.0
1937	35.2	3,721	105.7	986.3	35,481	36.0	90.3	35.3
1938	29.1	3,054	104.9	1,015.4	38,536	36.7	98.6	37.3
1939	28.0	2,399	85.7	1,043.4	40,936	39.2	83.6	38.6
1940	31.1	1,893	60.9	1,074.5	42,831	39.9	69.0	39.9
1941	32.5	1,969	60.6	1,107.0	44,798	40.5	69.0	40.6
1942	22.0	1,879	85.4	1,129.0	46,678	41.3	73.0	41.2
1943	20.3	1,485	73.2	1,149.3	48,165	41.9	79.6	42.0
1944	25.8	2,068	80.2	1,175.1	50,232	42.7	77.3	43.1
1945	26.6	2,087	78.5	1,201.7	52,319	43.5	82.2	43.6
1946	30.2	2,658	88.0	1,231.9	54,977	44.6	80.3	44.5
1947	33.1	2,465	74.5	1,265.0	57,441	45.4	86.2	45.7
1948	39.5	3,795	96.1	1,304.5	61,236	46.9	84.1	46.8
1949	39.0	3,188	81.7	1,343.5	64,422	48.0	79.0	47.5
1950	43.3	2,563	59.2	1,386.8	66,985	48.3	69.0	48.7
1951	46.0	4,414	96.0	1,432.8	71,399	49.8	71.7	49.2
1952	45.9	2,749	59.9	1,478.7	74,148	50.1	74.2	50.2
1953	49.3	3,296	66.9	1,528.0	77,444	50.6	60.0	50.6
1954	53.3	2,873	53.3	1,581.9	80,317	50.7	58.8	50.8
1955	56.7	3,185	56.2	1,638.6	83,502	51.0	53.5	50.9
1956	58.4	2,974	50.9	1,697.0	86,476	51.0	50.9	50.9
1957	53.4	2,425	45.4	1,750.4	88,901	50.8	50.9	50.9
1958	47.8	2,608	54.6	1,798.2	91,509	50.8		

Sources: Wells, U. S. Bureau of Mines; reserves, American Petroleum Institute.

TABLE IIa

BARRELS OF CRUDE OIL RESERVES DISCOVERED PER EXPLORATORY WELL, AS ESTIMATED FROM DRY HOLES, VERSUS CUMULATIVE DRY HOLES, 1859–1900, 1901–1958

Year	No. of Dry Holes (Thou.)	Disc. of Crude Oil Per Dry Hole (Thou. bbls.)	Cumulative Dry Holes (Thou.)	Cumulative Avg. Disc. Per Dry Hole (Thou. bbls.)	Disc. Per Dry Hole (Thou. bbls.—3-yr. Mov. Avg.)	Disc. Per Dry Hole Cumulative (Thou. bbls.—3-yr. Mov. Avg.)
1859–1900	32.5	120.1	32.5	120.1	120.1	120.1
1901–1905	17.6	77.9	50.1	106.7	77.9	106.7
1906	3.5	36.0	53.6	101.5		
1907	3.6	73.9	57.2	99.8	68.7	100.2
1908	2.9	96.2	60.1	99.6	94.2	99.2
1909	3.4	112.6	63.5	100.3	126.3	101.0
1910	3.0	170.0	66.5	103.4	194.2	104.6
1911	2.4	300.0	68.9	110.3	228.3	109.3
1912	2.9	214.8	71.8	114.5	200.6	112.5
1913	4.0	87.0	75.8	113.0	114.8	112.3
1914	3.9	42.6	79.7	109.6	84.3	110.9
1915	3.2	123.2	82.8	110.1	110.9	110.8
1916	4.1	166.9	87.0	113.4	119.0	111.5
1917	5.0	67.0	91.8	110.6	117.0	111.6
1918	5.6	117.1	97.4	111.0	109.4	111.5
1919	6.1	143.9	103.5	112.9	128.9	112.8
1920	7.5	125.7	110.0	114.8	158.6	116.5
1921	5.2	206.2	115.2	118.9	133.6	115.8
1922	5.2	68.8	120.4	116.8	132.3	117.6
1923	6.0	122.0	126.4	117.0	100.2	116.8
1924	5.6	109.6	132.0	116.7	163.7	119.8
1925	6.8	259.4	138.8	123.7	166.1	121.5
1926	8.3	129.0	147.1	124.0	249.9	127.6
1927	7.2	361.3	154.3	135.1	228.3	132.3
1928	7.2	194.6	161.5	137.7	325.9	141.1
1929	7.6	422.0	169.1	150.5	275.3	146.9
1930	6.2	209.4	175.3	152.6	235.8	151.4
1931	3.3	60.6	178.6	151.2	103.6	150.8
1932	3.4	25.3	182.0	148.8	91.5	149.8
1933	3.5	173.1	185.5	149.3	141.5	149.8
1934	4.8	226.0	190.3	151.2	204.4	151.2
1935	5.7	214.0	196.0	153.0	249.8	153.9
1936	5.7	309.3	201.7	157.5	374.5	160.4
1937	6.2	600.1	207.9	170.7	459.8	169.3
1938	6.5	469.8	214.4	179.7	472.6	178.5
1939	6.9	347.7	221.3	185.0	361.4	184.1
1940	7.1	266.6	228.4	187.5	294.7	187.5
1941	7.3	269.7	235.7	190.1	283.2	190.2
1942	6.0	313.2	241.7	193.1	271.8	192.4
1943	6.4	232.0	248.1	194.1	277.6	194.7
1944	7.2	287.2	255.3	196.8	268.5	196.7
1945	7.3	285.9	262.6	199.2	295.4	199.9
1946	8.5	312.7	271.1	202.8	283.5	202.2
1947	9.8	251.5	280.9	204.5	285.5	205.5
1948	11.9	318.9	292.8	209.1	272.5	208.1
1949	12.9	247.1	305.7	210.7	246.0	209.6
1950	14.9	172.0	320.6	208.9	223.8	210.3
1951	17.5	252.2	338.1	211.2	192.9	209.5
1952	17.8	154.4	355.9	208.3	194.9	208.8
1953	18.5	178.2	374.4	206.8	159.0	206.3
1954	19.9	144.4	394.3	203.7	159.0	203.9
1955	20.6	154.6	414.9	201.3	142.6	200.9
1956	22.3	128.7	437.2	197.8	134.6	197.8
1957	20.2	120.5	457.4	194.4	130.8	194.9
1958	18.2	143.2	475.6	192.4		

Sources: Well data: 1859–1900, 1901–17, U. S. Bureau of Mines, in *Petroleum Almanac*, National Industrial Conference Board, 1946, p. 11; 1905–17 dry holes estimated by multiplying the number of wells drilled per year by the five-year averages for dry hole percentages, as reported in the *World Petroleum Statistical Yearbook*, Vol. I, 1953–54, p. 98, as based on U. S. Bureau of Mines data; 1918–30 dry holes from *Petroleum Data Book*, Vol. I, 1947, p. D-12; 1931–53 from *World Petroleum Statistical Yearbook*, Vol. I, 1953–54, p. 98; 1954–58 from *World Oil*, February 15, 1959, p. 93. Reserve data: 1900–48, American Petroleum Institute in *World Oil*, February 15, 1958, p. 138; 1949–58, from American Petroleum Institute and American Gas Association Annual Reports on Reserves.

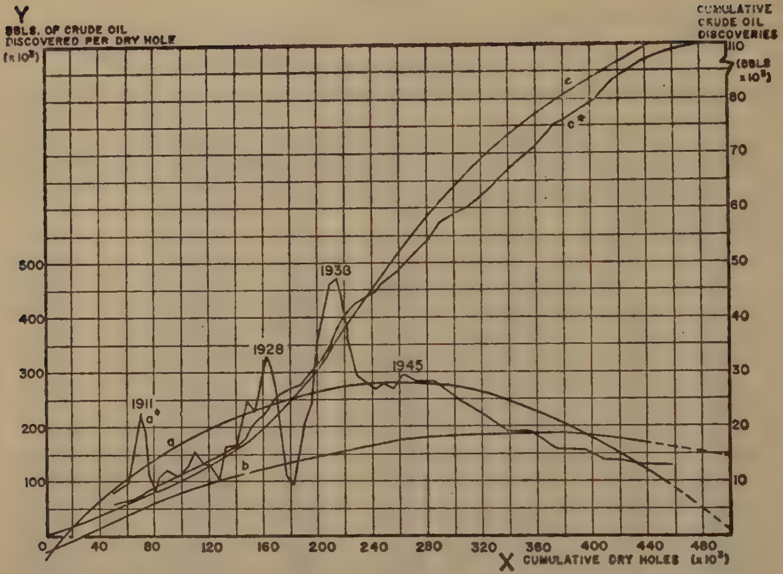

Chart II: Barrels of Crude Oil Reserves Discovered per Exploratory Well, as Estimated from Dry Holes, vs. Cumulative Dry Holes, 1907-1958. (Three-year moving averages) Line a*: Actual data on discoveries of crude oil per dry hole. Line a: Regression line of actual data on discoveries per dry hole. Line b: Regression line of cumulative average discoveries per dry hole. Line c*: Actual data on cumulative discoveries of crude oil. Line c: Regression line of cumulative discoveries of crude oil.

but it may perhaps be preferable to the use of the gross number of exploratory and developmental wells combined. Dry holes are sometimes used as an indirect way of estimating total exploratory wells[37] since a much higher ratio of dry holes occurs among exploratory wells than among developmental wells. However, this is not necessarily a dependable estimate of the number of exploratory wells. (For details, see the discussion of this point in Section I.) Even so, these results are considered sufficiently important to present in conjunction with other estimates of the trend of real finding costs in terms of barrels discovered per well.

The equation for discoveries per dry hole for the period 1907-58 is as follows:

$$Y' = -39.831 + 2.48636X - .00486607X^2$$

where Y' is thousands of barrels of reserves of crude oil discovered per dry hole

X is cumulative dry holes in thousands

The index of determination is .4705, indicating that 47.05 per cent of the total variation in the discoveries attributed to a dry hole is associated with the accompanying variation in the cumulative number of dry holes. The index of correlation is .6859. The standard error of estimate is 68,220 barrels, and the index of correlation is significant at the .001 level.

Chart II shows the same general course of discoveries as did Chart I. Peaks were reached in 1911, 1928, and 1945 (instead of 1947, as in Chart I). The chief point to be noted on this chart is the very close approximation of the actual course of discoveries to the theoretical fit for the period since 1941. Chart II contains five curves, two having been drawn up from actual data, and three having been statistically constructed from the actual data. Line a^* shows the actual data on the marginal productivity of exploratory wells as estimated from dry holes; line a is the curve fitted to these data, which shows the theoretical marginal productivity of exploratory wells. Line a or Y' is denoted mathematically as dD/dX, the first derivative of total cumulative discoveries D, with respect to cumulative dry holes, X. Line b shows the theoretical average productivity of exploratory wells as estimated from dry holes. Mathematically, it is simply the ratio of D to X for any value of X, i.e., the average number of barrels of crude oil discovered by all wells drilled up to that time. Line *b* is plotted chiefly in order to show its relationship to line *a*. Line *a* reaches a maximum in 1945, at which point the 255,482nd dry hole had a marginal productivity of 277,790 barrels of crude oil. After that point, marginal productivity continually decreases, although for a while, average productivity for all dry holes cumulatively continues to increase (line *b*). At about 390,000 dry holes, however (achieved sometime in 1954), the average productivity curve intersects the marginal productivity curve, and both curves then decline thereafter. This is a consequence of the functional relationship of average and marginal curves; as long as the marginal dry hole has a productivity above that of the cumulative average, the cumulative average productivity curve must increase, since the (higher) productivity of the marginal dry hole is being added in with that of all dry holes up to that point. But the marginal productivity continues to decline, and when the marginal productivity drops below the cumulative average productivity up to that point, the cumulative average productivity curve must correspondingly decline. Consequently, the point at which the marginal productivity curve intersects the average productivity curve is the point of maximum cumulative average productivity. Line c^* shows the actual data on cumulative total discoveries of crude oil. Line *c* shows the derived curve which corresponds to the actual data. Mathematically, line *c* is the integral of line *a*, or the integral of dD/dX, which is measured in terms of D, cumulative total discoveries of crude oil in billons of barrels.

It is to be noted that, according to Chart II, the level of zero discoveries per dry hole will be reached before 490,000 dry holes have been drilled. This extrapolation thus implies a degree of pessimism bordering upon absurdity, inasmuch as 490,000 dry holes will no doubt have been drilled by late 1959. While it would be far-fetched to place much reliance upon any single measure such as this, other ways of estimating ultimate reserves merely substitute different types of guesswork, which often do not have the support of such extensive historical data as underlie the present computation. A glance at Chart II, however, will serve to warn us that since about 1955, the rate of actual decline in discoveries has not been as rapid as the extrapolated parabolic curve would call for.

Chart III presents the information on discoveries of crude oil per dry hole in yet another manner. Here discoveries per dry hole have been plotted versus cumulative discoveries of

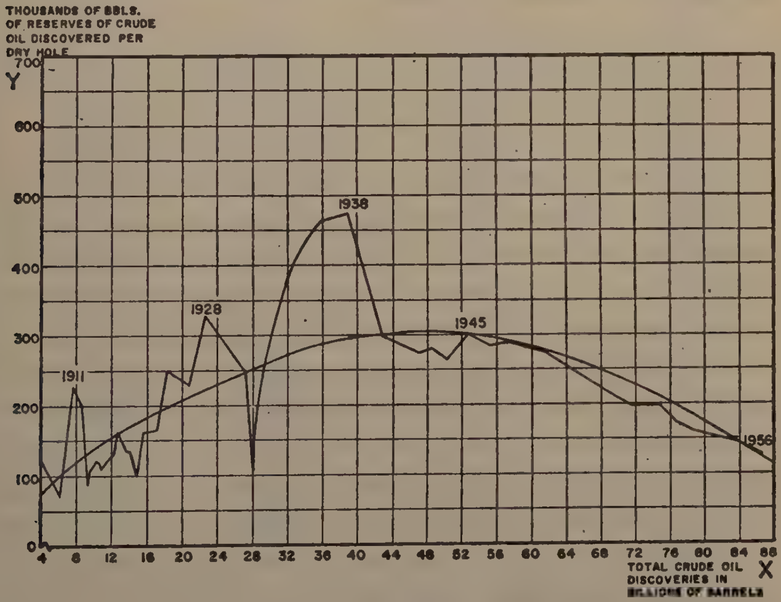

Chart III: Barrels of Crude Oil Reserves Discovered per Dry Hole, vs. Cumulative Crude Oil Discoveries, 1907-1957. (Three-year moving averages.)

crude oil, in billions of barrels. Cumulative discoveries are employed here as the independent variable in order to illuminate another aspect of diminishing returns in drilling activities. The greater the volume of oil that has been discovered, the smaller is the remaining quantity to be found. Cumulative dry holes do not serve to place the relationship in as sharp a focus as do cumulative discoveries, since each dry hole is counted as homogeneous with every other dry hole, but as the average discovery rate of a dry hole declines, cumulative discoveries do not increase relatively as rapidly as cumulative dry holes. The over-all fit of the equation to the data is better than in the case of Chart II, the fit between 1940 and 1954 being exceptionally close. The equation of this parabolic curve is as follows:

$$Y' = 29.796 + 11.65324X - .124277X^2$$

where Y' is discoveries of crude oil per dry hole in thousands of barrels
X is cumulative discoveries of crude oil in billions of barrels

The index of determination is .6043, indicating that 60.43 per cent of the variation in the discoveries attributable to a dry hole is associated with the accompanying variation in the cumulative number of dry holes. The index of correlation is .7773. The standard error of estimate is 58,980 barrels, and the correlation index is significant at the .001 level.

If we extrapolate this curve in an attempt to predict the point at which cumulative discoveries will reach a maximum and new discoveries will cease, we obtain results that are approximately the same as those of Chart II. But these extrapolations seem too pessimistic in the light of the fact that since 1954 the rate of discovery, although continuing to decline, has not declined at as rapid a rate as our parabolic estimating equation would indicate. Here the situation is much the same as it was in Chart II. This circumstance

TABLE III

BARRELS OF CRUDE OIL RESERVES DISCOVERED PER DRY HOLE VS. CUMULATIVE CRUDE OIL DISCOVERIES, 1907–1957

Year	Discoveries of Crude Oil Per Dry Hole (Thousand barrels)	Average No. of Bbls. Per Dry Hole Cumulative Basis (Thousand barrels)	Cumulative Crude Oil Discoveries (Billion barrels)
	—3-year Moving Averages—		
1907	68.7	100.2	5.71
1908	94.2	99.2	6.00
1909	126.3	101.0	6.37
1910	194.2	104.6	6.88
1911	228.3	109.3	7.60
1912	200.6	112.5	8.22
1913	114.8	112.3	8.57
1914	84.2	110.9	8.74
1915	110.9	110.8	9.12
1916	119.0	111.5	9.87
1917	117.0	111.6	10.15
1918	109.4	111.5	10.81
1919	128.9	112.8	11.69
1920	158.6	115.5	12.63
1921	133.6	116.8	13.70
1922	132.3	117.6	14.06
1923	100.2	116.8	14.79
1924	163.7	119.8	15.41
1925	166.1	121.5	17.17
1926	249.9	127.6	18.24
1927	228.3	132.3	20.84
1928	325.9	141.1	22.24
1929	275.3	146.9	25.45
1930	235.8	151.4	26.50
1931	103.6	150.9	27.00
1932	91.5	149.8	27.09
1933	141.5	149.8	27.69
1934	204.4	151.2	28.78
1935	249.8	153.9	30.00
1936	374.5	160.4	31.76
1937	459.8	169.3	35.48
1938	472.6	178.5	38.54
1939	361.4	184.1	40.92
1940	294.7	187.5	42.83
1941	283.2	190.2	44.80
1942	271.8	192.4	46.68
1943	277.6	194.7	48.17
1944	268.5	196.7	50.23
1945	295.4	199.9	52.32
1946	283.5	202.2	54.98
1947	285.5	205.4	57.44
1948	272.5	208.1	61.23
1949	246.0	209.6	64.42
1950	223.8	210.3	66.99
1951	192.9	209.5	71.34
1952	194.9	208.8	74.15
1953	159.0	206.3	77.44
1954	159.0	203.9	80.32
1955	142.6	200.9	83.50
1956	134.6	197.8	86.48
1957	130.8	194.9	88.90

Sources: Cumulative discoveries, American Petroleum Institute; discoveries per dry hole, see Table IIa.

probably arises for two reasons that make the parabolic decline curve unsuitable for the present stage of diminishing returns to exploration.

First, as was mentioned in connection with Chart I, we are probably dealing with three separate eras in exploration, the declining stages of each of which would no doubt be characterized by a decreasing rate of decline as smaller and smaller pools continue to be found from year to year. If perfect knowledge of exploration opportunities prevailed, the decline would probably be rapid at the end, in accordance with the parabolic form of equation, but since knowledge is imperfect, it is probable that the decline would be a rather longer and more gradual process, a mopping-up operation on small pools that had been by-passed by earlier exploration programs, and the resulting decline curve would be more likely to have the form of a declining hyperbola which made an asymptotic approach to the zero level of discoveries over a very long period of time.

Second, our measure of exploration in terms of dry holes is by no means a suitable substitute for a measurement in terms of exploratory wells proper. In fact, it may well be that the very close fit that prevailed between 1941 and 1954 is somewhat fortuitous, although much of the closeness of fit must also be interpreted along the lines of the data in Charts I and II for the last 20 years. That is to say, during this period, exploration was carried on more intensively, or more "professionally," and fewer random fluctuations were experienced because the great majority of firms had been forced to use the best available exploration techniques in a consistently intensive manner.

Chart IV represents still another attempt to measure the trend in the real cost of finding crude oil reserves. In this

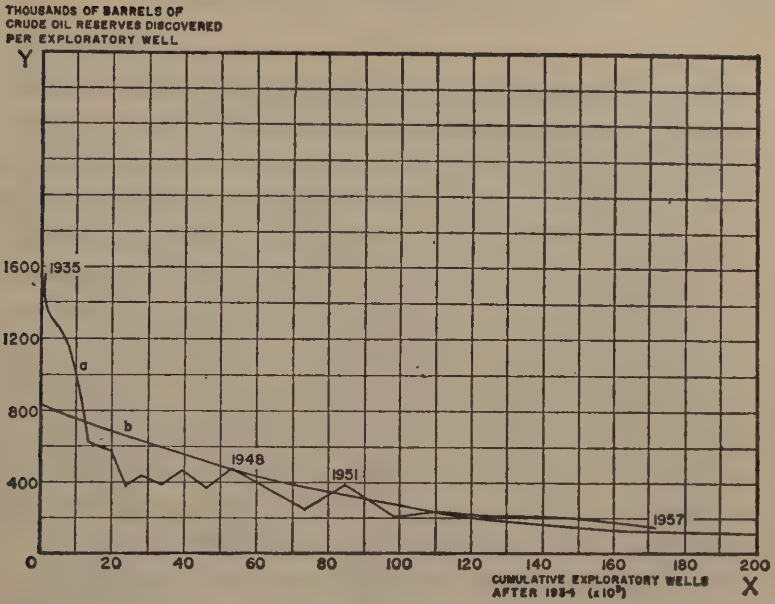

Chart IV: Barrels of Crude Oil Reserves Discovered per Exploratory Well, vs. Cumulative Exploratory Wells since 1934, for 1935-1957. Line a: Actual data. Line b: Regression line of actual data.

instance we have traded the advantage of a longer historical perspective for the probably greater advantage of a consistent definition of our unit of exploratory outlay. Here we measure the average number of barrels of crude oil discovered per exploratory well, in relationship to the cumulative number of exploratory wells drilled since 1934. Estimates of the number of exploratory wells can be made with sufficient accuracy back to 1935, and although this limits the time period covered by our trend calculations, we have the advantage of being able to allocate total crude oil discoveries to exploratory wells proper, the best single measure of discovery effort.

If we look at the actual data for 1935-1957, we note that it contrasts somewhat with the data of the first three charts for the period since 1935. On the basis of dry hole data, the period began with a pronounced increase in discoveries per dry hole from 1935 to a peak in 1938, and then declined to a secondary peak in 1945, with an almost unbroken decline since that time. The data on exploratory wells proper, however, show a precipitous decline from the very beginning of the period, 1935, until 1943, after which a gentler but pronounced rate of decline has prevailed, broken only by upturns in 1948 and 1951. It should be noted that this curve is drawn up on the basis of annual observations rather than the three-year moving averages previously employed; if three-year moving averages were used in Chart IV as well the downward trend would be virtually uninterrupted.

A logarithmic decline curve was fitted to the data of Chart IV, and the decline that results seems more in line with our *a priori* expectations as to the later stages of diminishing returns to drilling activity, and also more consistent with the most recent observations in Charts II and III. The form of the logarithmic equation is:

$$\log Y' = 2.92651 - .4888821 \times 10^{-5}X$$

where Y' is discoveries of crude oil reserves per exploratory well in thousands of barrels

X is cumulative number of exploratory wells since 1934.

The index of determination is .7769 and the index of correlation is .8814. The standard error of estimate is 13,640 barrels and the correlation index is significant at the .001 level.

In estimating the total discoveries of crude oil as a function of cumulative exploratory wells, it is necessary to integrate Y' and add as the constant of integration the

Table IV

Barrels of Crude Oil Reserves Discovered Per Exploratory Well vs. Cumulative Exploratory Wells Since 1934

Year	Cumulative Exploratory Wells Since 1934	Discoveries of Crude Oil Per Exploratory Well (Thousand barrels)
1935	787	1,550
1936	1,812	1,375
1937	4,772	1,280
1938	7,410	1,158
1939	10,112	888
1940	13,150	623
1941	16,414	603
1942	19,626	585
1943	23,634	371
1944	28,430	431
1945	33,746	397
1946	39,515	461
1947	46,290	364
1948	54,303	474
1949	63,361	352
1950	73,667	249
1951	85,423	375
1952	97,848	221
1953	111,161	248
1954	124,258	219
1955	139,195	192
1956	155,368	184
1957	170,075	165

Sources: Wells 1935–37, J. E. Swearingen and J. W. Boatwright, "Meeting Future Petroleum Demands," in *Hearings on H.R. 4294*, 83rd Congress, first session, p. 987; 1938–57, F. H. Lahee, in July issues of the *Bulletin of the American Association of Petroleum Geologists;* discoveries, American Petroleum Institute, in *World Oil.*

amount of cumulative discoveries made before 1935, a figure of some 30 billion barrels. We find that the ultimate level of discoveries to be expected will be some 103,334,000,000 barrels, to be discovered in progressively smaller amounts over the indefinitely prolonged future as the logarithmic curve approaches more and more closely to zero.

Chart V puts the same information in a slightly different perspective. Here the declining rate of discoveries per exploratory well is expressed in relation to the cumulative discoveries of crude oil. It is interesting, if rather futile, to speculate on the trend which could be obtained prior to 1935 if the necessary data were available. No doubt the years 1935-38 were years of exceptionally large discoveries, but it would be interesting to know how many exploratory wells were drilled in the earlier years, and whether or not the real trend, for each of the three discovery "eras" was actually one of continually decreasing returns from the very beginning of the era. Unfortunately we cannot measure the returns per actual exploratory well. Chart V also shows how

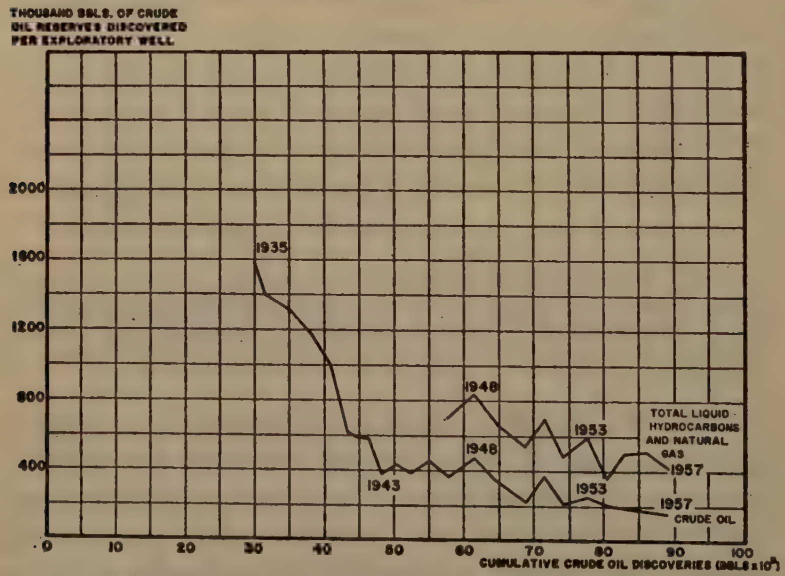

CHART V: Barrels of Crude Oil Reserves Discovered per Exploratory Well vs. Cumulative Discoveries of Crude Oil, 1935-1957; Barrels of Total Liquid Hydrocarbons and Natural Gas Discovered per Exploratory Well vs. Cumulative Discoveries of Crude Oil, 1947-1957.

the picture is changed if natural gas and natural gas liquids are added in with crude oil, on the basis of the crude-oil equivalent of the BTU's represented by the other liquid hydrocarbons and natural gas. This increases the average level of discoveries by almost 100 per cent and greatly increases the year-to-year fluctuation, but there is still a notable decline over the years 1947-58, which are the only years for which acceptable data on the volume of natural gas discoveries are available.

After having surveyed the above evidence of trends in the real cost of finding reserves, from the vantage point of the longest obtainable historical perspective, it is probably best to undertake a detailed investigation of the available statistics relating to the real costs and the real productivity of true exploratory wells, and to consider briefly the relation-

TABLE V

BARRELS OF TOTAL LIQUID HYDROCARBONS AND NATURAL GAS DISCOVERED PER EXPLORATORY WELL, 1947–1957

Year	Total Liquid Hydrocarbons & Natural Gas (Million bbls.)	Number of Exploratory Wells	Bbls. Found Per Expl. Well (Thousands)
1947	4,770	6,775	704.1
1948	6,850	8,013	854.9
1949	5,938	9,058	655.6
1950	5,571	10,306	540.5
1951	8,137	11,756	692.2
1952	6,002	12,425	483.1
1953	7,927	13,313	595.4
1954	4,776	13,097	364.7
1955	7,467	14,937	498.6
1956	8,389	16,173	518.7
1957	6,145	14,707	417.8

Sources: Wells, F. H. Lahee, in July issues of the *Bulletin of the American Association of Petroleum Geologists*; Reserves, American Petroleum Institute and American Gas Association, in *World Oil*.

ship between exploratory and development wells. Before investigating the details of these special classes of wells, however, there are two additional series on the real cost of finding reserves which extend over a sufficiently long period of time to confer upon them some historical interest. Neither of these series presents a clear picture as far as the assessment of specific cost trends is concerned, but each makes its contribution to the overall picture of increasing real costs, and emphasizes the fact that such a picture must at present be built up from a large number of sources of only indirect immediate relevance to the cost trend problem.

The first of these historical series has been compiled from a number of sources and purports to show the trend in the average depth of all wells drilled, from 1860 to 1958. These data are contained in Chart VI, where it is shown that the average depth of wells drilled did not exceed 2,000 feet until 1916-20, but that average depths have increased quite rapidly since 1931. A straight-line curve was fitted to the 1931-58 data, and the following equation was obtained:

$$Y' = 3{,}410.6 + 64.67X$$

where Y′ is the average depth of wells (excluding service wells) in feet
X is time in years (1945 = 0)

The standard error of estimate is 132.1 feet. This equation indicates that the average depth of all wells in the United States is increasing by 64.67 feet per year. It is not certain but it is rather likely from the data presented in Chart VI, that the long-run trend of average well depth in the industry has been to increase at a somewhat increasing rate, with the increase in this rate becoming somewhat more pronounced since about 1930. If year-to-year data were only available prior to 1930, it would be rewarding to attempt to fit an exponentially increasing curve to this data. As it is, an average increase of 64.67 feet per year per well is a

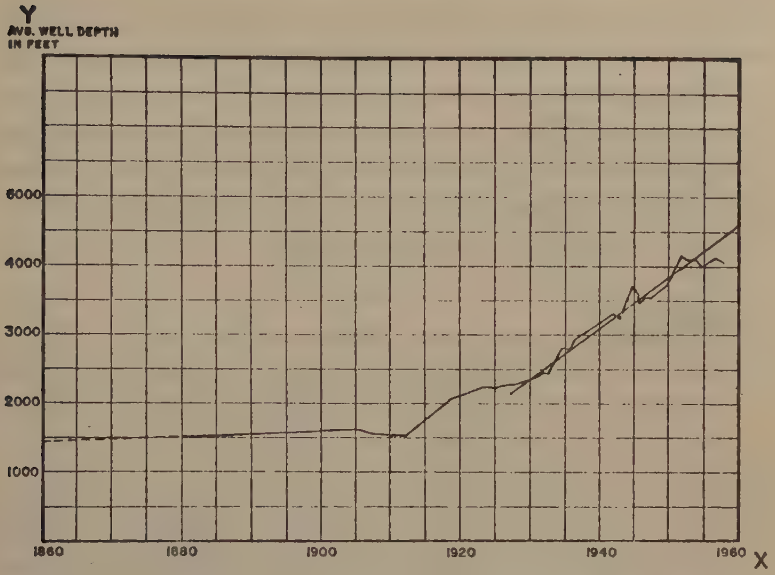

CHART VI: Average Depth of All Wells Drilled, 1860-1958. (Excludes Service Wells.)

very sizeable factor making for increasing costs. This can be seen from the data on costs of drilling by depth range, developed by the Joint Association Survey on Drilling Costs. If we interpolate on the basis of these data from the Survey, we find that the total cost of a well 4,052 feet deep (the 1958 average depth) would be $26,440. A 64.67 foot annual increase in depth would bring the average depth of the 1959 well to about 4,117 feet, at which level a total cost of $28,060 for drilling alone could be expected. This is an increase of $1,620 per well at 1953 cost levels. Since the Survey data show that the total cost increases more than proportionately with increasing depth of well, total costs per well can therefore be expected to increase more rapidly than average footage in the future.

The second of these historical series shows the number of barrels of crude oil reserves found per foot drilled, from 1925 through 1957, and also shows the number of barrels of crude oil equivalent discovered per foot drilled, when crude oil, natural gas liquids, and natural gas are all converted into equivalent barrels of crude oil on the basis of their relative BTU content. These data are shown in Chart VII, and bear some resemblance to the data presented in Charts I, II, and III, the chief difference being that the data of Chart VII have not been subjected to the moving-average process. The advantage that this chart has over Chart I is that it shows the effect of the increasing average depth of wells, the produc-

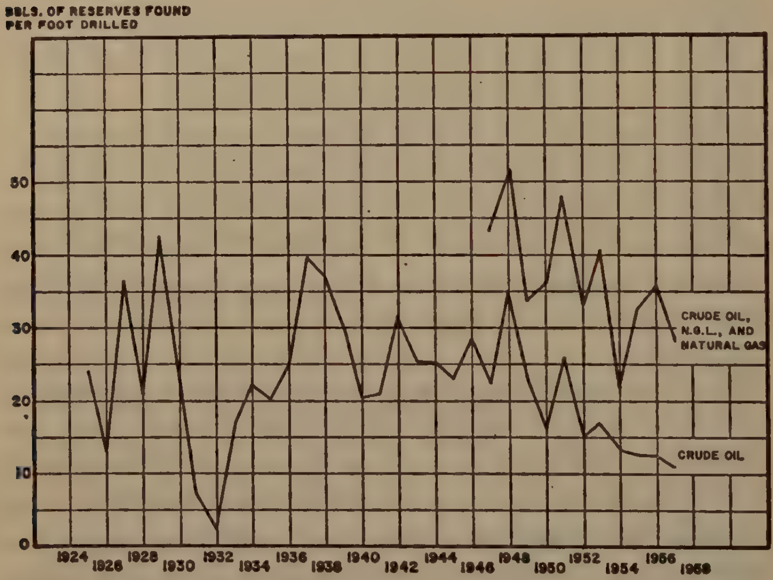

Chart VII: Barrels of Reserves Discovered per Foot Drilled: Crude Oil, 1925-1957; Crude Oil, Natural Gas Liquids, and Natural Gas, 1947-1957.

TABLE VI

BARRELS OF RESERVES DISCOVERED PER FOOT DRILLED: CRUDE OIL, 1925–1957; CRUDE OIL, NATURAL GAS LIQUIDS, AND NATURAL GAS, 1947–1957

Year	Total Feet Drilled* (Thousands)	Total Crude Oil Reserves Found (Million Barrels)	Bbls./Ft.	Total Discoveries of Crude Oil, Natural Gas Liquids, and Natural Gas (Million Barrels)	Total Discoveries of Crude Oil, Natural Gas Liquids, and Natural Gas, in Equivalent Barrels of Crude Oil Per Foot Drilled
1925	73,677	1,763	23.93		
1926	81,186	1,071	13.19		
1927	71,850	2,601	36.20		
1928	66,033	1,401	21.22		
1929	75,879	3,207	42.26		
1930	62,189	1,298	20.87		
1931	36,500	251	6.78		
1932	45,331	85	1.88		
1933	36,665	606	16.53		
1934	48,986	1,085	22.15		
1935	59,483	1,220	20.51		
1936	71,169	1,763	24.77		
1937	93,594	3,722	39.77		
1938	82,887	3,054	36.85		
1939	80,679	2,399	29.74		
1940	89,058	1,893	20.55		
1941	93,930	1,969	20.96		
1942	59,575	1,879	31.54		
1943	58,320	1,485	25.46		
1944	82,227	2,068	25.15		
1945	91,486	2,110	23.06		
1946	93,949	2,658	28.29		
1947	109,577	2,464	22.49	4,770	43.53
1948	133,704	3,795	34.63	6.850	59.23
1949	136,796	3,188	23.30	5,938	33.59
1950	157,310	2,563	16.29	5,571	36.24
1951	170,298	4,414	25.92	8,137	47.78
1952	183,494	2,749	14.98	6,002	32.71
1953	195,548	3,296	16.86	7,927	40.54
1954	218,986	2,873	13.12	4,776	21.81
1955	228,530	2,871	12.60	7,467	32.67
1956	235,386	2.974	12.63	8,389	35.64
1957	219,404	2,425	11.05	6,145	28.01

Sources: Reserves, American Petroleum Institute; footage, U. S. Bureau of Mines, 1925–26 in *Petroleum Almanac*, p. 15; 1927–38 in *Petroleum Data Book*, 1947, p. D-40; 1939–57 in *World Oil*, February 15, 1958, p. 139.

* Excludes service wells.

tivity per foot drilled in the late 1920's is actually greater than that of 1937, although on a per-well basis, the 1937-38 peak is considerably higher. For crude oil alone, the trend since the late 1930's is clearly a downward one, although it was broken by higher values for the years 1948 and 1951, and to a lesser extent, by 1946 and 1953. Since 1953 the trend has been continually downward, falling from 16.86 barrels per foot in 1953, to 11.05 barrels per foot in 1957. For crude oil, natural gas liquids, and natural gas, the trend from 1947 through 1957 has on the whole declined at least as steeply, although the fluctuations around the trend line of decline that might be fitted to these eleven years are inordinately large, much of this fluctuation being attributable to extensions and revisions of natural gas reserve discoveries for prior years. It is useful to note that, even if natural gas liquids and natural gas are included with crude oil discoveries, the downward orientation of the trend since 1947 is not altered, although the dispersion around this trend is greatly increased. Obviously we can make no valid conclusions about the trend unless we have reliable data on reserves of natural gas liquids and natural gas before 1947, but unfortunately these data are not available.

Tables VII and VIII represent an attempt to provide supplementary information on the ratios in which crude oil, natural gas liquids, and natural gas discoveries have been encountered in the past twenty years. One is immediately struck by the extreme variability in these ratios from year to year. First, let us consider the ratio of new discoveries of natural gas liquids to new discoveries of crude oil. In 1935 this ratio was less than one-half of one per cent, but gradually increased, with extreme year-to-year variations, to a level of about 19 per cent in 1951, and to some 31 per cent in 1957. If we compare extensions and revisions of natural gas liquids discoveries with extensions and revisions of crude oil discoveries, we find that the same pattern of extreme variation is present, although on the whole the trend has been upward since about 1937. There seems to be no real stability in this ratio, however, for the ratio was 28.6 per cent in 1956 and 0.5 per cent in 1957.

TABLE VII

RATIO OF TOTAL DISCOVERIES, EXTENSIONS, AND REVISIONS OF NATURAL GAS LIQUIDS AND NATURAL GAS TO CRUDE OIL
(Millions of Barrels)

Year	New Discoveries			Revisions & Extensions			(2) ÷ (1)	(3) ÷ (1)	(5) ÷ (4)
	Crude	NGL*	Natural Gas	Crude	NGL*	Natural Gas			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1935	950	5		270	60		.0053		.2222
1936	850	10		913	37		.0118		.0405
1937	929	11		2,793	57		.0118		.0204
1938	810	15		2,244	81		.0185		.0361
1939	341	19		2,058	82		.0557		.0398
1940	286	29		1,607	78		.1014		.0485
1941	430	25		1,539	81		.0581		.0526
1942	260	20		1,619	91		.0769		.0117
1943	282	63		1,203	62		.2234		.0515
1944	511	4		1.557	17		.0078		.0109
1945	420	20		1.690	180		.0476		.1065
1946	244	79		2,414	44		.3238		.0182
1947	445	59	632	2,019	193	1,422	.1326	1.420	.0956
1948	396	65	765	3,399	406	1,820	.1641	1.932	.1194
1949	890	93	855	2,298	394	1,509	.1045	.961	.1715
1950	565	58	533	1,998	708	1,710	.1027	.943	.3544
1951	389	75	563	4,025	649	2,437	.1928	1.447	.1612
1952	496	82	1,003	2,253	475	1,693	.1653	2.022	.2108
1953	592	96	1,312	2,704	748	2,575	.1622	2.216	.2766
1954	586	86	921	2,287	23	875	.1468	1.572	.0101
1955	477	67	1,060	2,394	448	3,021	.1405	2.222	.1871
1956	467	94	1,044	2,506	716	3,561	.2013	2.235	.2857
1957	416	129	1,660	2,009	9	2,060	.3101	3.990	.0054

* Natural Gas Liquids.
Sources: American Petroleum Institute and American Gas Association; 1935–1946 data presented by H. J. Struth in *World Petroleum*, July 1954, p. 60.

Two other series have been computed for purposes of comparison. The ratio of total additions to natural gas liquids discoveries to total additions to crude oil discoveries has

TABLE VIII

RATIOS OF TOTAL DISCOVERIES OF CRUDE OIL TO TOTAL DISCOVERIES OF TOTAL LIQUID HYDROCARBONS AND NATURAL GAS, 1935–1957

Year	Total Disc. of Crude Oil (Million Barrels)	Total Disc. of Natural Gas Liquids (Million Barrels)	Total Disc. of Natural Gas (Million Barrels)	(2) – (1)	(3) – (1)	3-Yr. Moving Average of (4)	3-Yr. Moving Average of (5)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
1935	1,220	65		.0533			
1936	1,763	47		.0267		.0328	
1937	3,722	68		.0183		.0255	
1938	3,054	96		.0314		.0306	
1939	2,399	101		.0421		.0433	
1940	1,893	107		.0565		.0505	
1941	1,969	106		.0538		.0547	
1942	1,879	101		.0537		.0639	
1943	1,485	125		.0842		.0494	
1944	2,068	21		.0102		.0631	
1945	2,110	200		.0948		.0394	
1946	2,658	35		.0132		.0701	
1947	2,464	252	2,054	.1023	.834	.0797	
1948	3,795	471	2,585	.1241	.681	.1159	.752
1949	3,188	387	2,364	.1214	.742	.1815	.766
1950	2,563	766	2,243	.2989	.875	.1948	.766
1951	4,414	724	3,000	.1640	.680	.2218	.845
1952	2,749	557	2,696	.2026	.981	.1974	.947
1953	3,296	744	3,887	.2257	1.199	.1423	.928
1954	2,873	107	1,796	.0372	.625	.1474	1.076
1955	2,871	515	4,081	.1794	1.424	.1630	1.210
1956	2,974	810	4,605	.2724	1.630	.1696	1.513
1957	2,425	138	3,720	.0569	1.696		

Sources: American Petroleum Institute and American Gas Association; 1935–1946 data based on data presented by H. J. Struth, in *World Petroleum*, July 1954, pp. 60, 62.

been computed, and also the ratio of the total additions to natural gas discoveries to total additions to crude oil discoveries, both of these series being computed on the basis of three-year moving averages to eliminate extreme fluctuations. The first of these two series seems to have increased from about three per cent in 1936-38 to over 22 per cent in 1950-52, and to have decreased to about 15 per cent since that time. The second of the two series shows the most interesting and consistent trend present in the entirety of these data. The ratio of total discoveries of natural gas to total discoveries of crude oil has doubled in ten years, from 75.2 per cent in 1947-49, to 151.3 per cent in 1955-57. In part this is a consequence of deeper drilling, it would seem, for there is a familiar phrase in the industry to the effect that "the deeper the crude, the lighter the crude." In part, however, it would seem to indicate that different types of formations are now being more widely explored than was formerly the case. At any rate, this phenomenon points up the increasing urgency of the need for devising a more satisfactory way of dealing with the joint-product dilemma.

Turning next to the detailed consideration of the statistics on exploratory wells, we may first note that the costs of finding oil through a program of exploratory drilling will vary with (1) the average depth of wells, (2) the percentage of dry holes among exploratory wells, and (3) the average size of oil or gas pools discovered. All of these variables can be combined when the trend of discoveries per exploratory foot drilled is computed, but it is instructive to consider the first and second of these variables separately before investigating the net result of all of them as it affects discoveries per exploratory foot.

Chart VIII shows the number of exploratory wells and the total footage drilled for the period 1937-57. Both series are difficult to analyze statistically because of the indications which each presents of a break in an upward trend, the period of the break being somewhere between 1954 and 1956. Footage and total wells both demonstrate an exponential rate of increase up until about 1954, when the trend is clearly broken without the establishment of any definite new trend. If we can take 1954 as the end of the trend, we can compute the historical trends of total exploratory wells and total exploratory footage for the period 1937-54. This would be of interest, and would be useful chiefly in the event that the 1937-54 trend might be resumed in the near future, after of course allowing for the break in the series. It is probably not likely that such a rate of increase

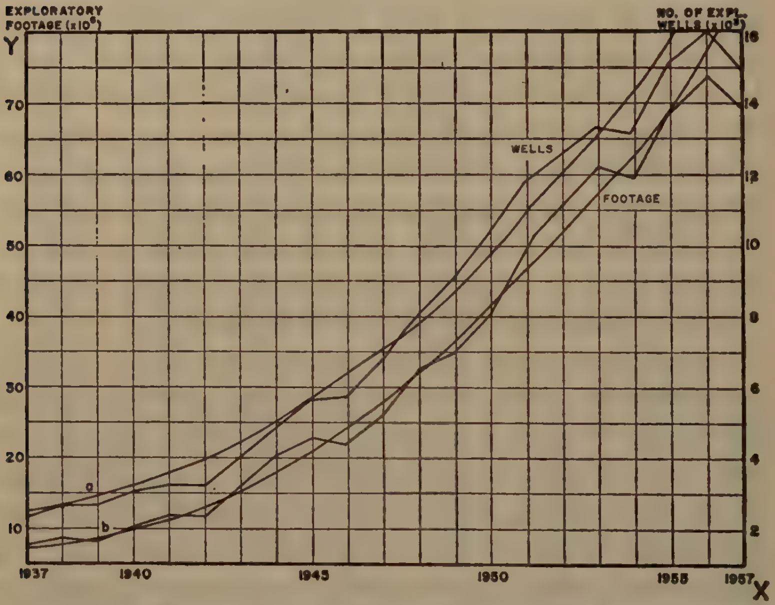

CHART VIII: Exploratory Wells: Number and Total Footage Drilled, 1937-1957. Line a: Total number of exploratory wells drilled. Line b: Total footage drilled.

would be precisely resumed, although if the decline in the average discoveries per exploratory well predicted in Charts III and IV is to come about, the increase in total exploratory wells and footage must be at least as great as that experienced in the period 1937-54, since discoveries per well and per foot will continue to fall.

The parabolic equation for the number of wells drilled is as follows:

$$Y' = 7{,}688.15 + 779.16X + 17.3529X^2$$

where Y' is the number of exploratory wells drilled per year
X is time in years ($1948 = 0$)

The standard error of estimate is 725.8 wells. This curve increases quite rapidly; for the year 1959, for example, the increase in exploratory wells over 1958 would be 1,471 wells, a sizeable but not impossible increase, especially when one takes into account the increased number of wells needed to maintain reserves when the average size of oil pools found continues to decrease.

A logarithmic equation was found to provide the best fit to the data on total exploratory footage. The equation is as follows:

$$\log Y' = 4.40511 + .051965X$$

where Y' = thousands of feet of exploratory wells drilled per year
X = time in years ($1947 = 0$)

The standard error of estimate is 114,900 feet. This equation produced a very good fit for the data through 1955. The same may be said for this series that was said for the preceding equation on exploratory wells. Future reserve requirements must be met, and even if demand does not increase at as rapid a rate as it has in the past decade, decreasing success rates in finding reserves may be such as to indicate the relevance of the resumption of such a rate of drilling as is given by the above equation.

Chart IX gives the average depth of exploratory wells, classified into five groups, for the period 1938-57. For condensate wells, a very small group, the average depth of well has been increasing rapidly since 1953, although the peak level of 1948 has not been regained. The other four categories, gas-producing exploratory wells, oil producing wells,

TABLE IX

EXPLORATORY WELLS: NUMBER AND TOTAL FOOTAGE DRILLED, 1937–1957

Year	Total Exploratory Footage (Thousand feet)	Total Exploratory Wells
1937	N.A.	2,322
1938	8,860	2,638
1939	8,793	2,702
1940	10,254	3,038
1941	11,615	3,264
1942	12,124	3,212
1943	15,720	4,008
1944	20,226	4,796
1945	23,030	5,316
1946	22,198	5,769
1947	26,393	6,775
1948	32,741	8,013
1949	34,798	9,058
1950	40,175	10,306
1951	49,344	11,756
1952	55,615	12,425
1953	60,703	13,313
1954	59,581	13,097
1955	69,173	14,937
1956	73,981	16,173
1957	69,136	14,707

Source: F. H. Lahee, in July issues of the *Bulletin of the American Association of Petroleum Geologists*.

total exploratory wells, and dry exploratory wells, are closer together in average depth, and have been increasing in depth, on the whole, 80 or more feet per year since 1938. It is interesting to note that the average depth of dry wells has always been lower than that of any producing group; that oil producers have generally had the highest average depth since 1945 (with the exception of four years in which they were exceeded by the relatively small group of gas producers), and that among those four years are included three of the last four years in the series: 1954, 1956, and 1957.

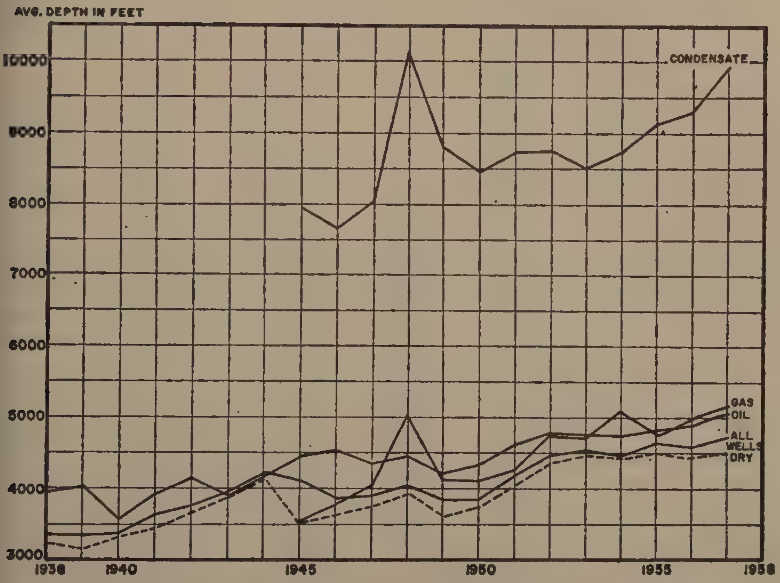

Chart IX: Exploratory Wells: Average Depth of Dry Wells, Oil Finding Wells, Gas Wells, Condensate Wells, and Total Exploratory Wells, 1938-1957.

Chart X reveals an even more pronounced trend in the

TABLE X

DEVELOPMENT WELLS: PERCENTAGE DISTRIBUTION BY DRILLING CATEGORIES; EXPLORATOR

Year	Per Cent of All Developmental Wells				Per Cent of Exploratory Wells				
	Dry	Oil Prod.	Gas Prod.	Condensate Producers	Outposts	New-Pool Wildcats	Deeper-Pool Tests	Shallower-Pool Tests	New-Field Wildcats
1937									
1938	16.0	75.7	8.2						
1939	17.2	73.7	9.1						
1940	15.7	75.1	9.1						
1941	16.5	72.4	11.1						
1942	18.7	67.9	13.4						
1943	22.3	66.2	11.5		17.0		3.7		
1944	17.2	67.3	15.5		15.7	14.7	4.5	0.5	
1945	16.1	70.6	13.0	0.3	21.6	16.1	7.5	0.7	54.1
1946	16.1	71.1	12.3	0.5	23.6	14.8	6.8	0.5	54.4
1947	17.5	70.4	11.2	0.9	22.8	17.9	7.9	0.6	51.3
1948	18.9	72.7	7.9	0.8	22.0	18.3	5.4	0.6	53.6
1949	19.6	71.7	7.8	0.8	23.8	20.6	5.5	1.0	49.1
1950	20.5	71.9	6.5	1.0	24.5	19.7	3.2	1.3	51.3
1951	22.8	69.0	7.5	0.7	21.3	20.8	3.6	1.6	52.6
1952	23.8	67.7	7.9	0.5	19.5	21.4	3.5	1.6	53.9
1953	22.7	68.4	8.4	0.5	22.7	21.0	2.5	1.1	52.0
1954	26.0	65.7	7.1	1.2	20.1	18.7	3.3	1.5	56.3
1955	21.6	70.6	7.0	0.8	21.5	19.6	3.1	1.6	54.3
1956	21.4	69.0	8.7	0.7	22.4	20.0	2.9	0.9	53.8
1957	22.0	68.0	8.5	1.2	21.9	20.0	2.8	0.8	54.5

Sources: All exploratory well data from F. H. Lahee, in July issues of the *Bulletin of The America*
ssociation of Petroleum Geologists. Development well totals were derived by subtracting Lahee's dat
n total exploratory wells from *World Oil's* data on total wells and total footage drilled (service wel

average depth of exploratory wells. The average depth of successful new field wildcat wells has been increasing much more rapidly than the depth of any other class of exploratory wells, and significantly more rapidly than the average for all new field wildcats taken together. Successful new field wildcats are of course the most crucial wells for future reserves, and this marked increase in depth is perhaps the most striking evidence that can be presented to demonstrate the increasing

TABLE X

ELLS: PERCENTAGE DISTRIBUTION AND AVERAGE DEPTH, BY DRILLING CATEGORIES, 1938–1957

Average Depth of Exploratory Wells (Feet)							
All Oil Prod.	All Dry Wells	Gas Prod.	Condensate Producers	All New Field Wildcats	Dry New Field Wildcats	Successful New Field Wildcats	All Expl. Wells
				3,713	3,692	3,883	
3,982	3,232	4,840		3,313	3,218	4,095	3,359
4,040	3,162	4,000		3,153	3,121	3,465	3,331
3,586	3,309	5,125		3,269	3,237	3,523	3,375
3,918	3,465	6,950		3,232	3,167	3,779	3,559
4,158	3,664	8,566		3,602	3,515	4,264	3,775
3,903	3,881	4,571		4,111	4,016	4,765	3,922
3,925	4,113	3,571		4,200	4,127	4,795	4,217
4,450	3,530	3,555	7,940	4,402	4,312	5,082	4,103
4,534	3,659	3,834	7,650	4,007	3,879	5,084	3,854
4,364	3,747	4,021	8,028	4,200	3,970	5,322	3,896
4,447	3,902	5,035	10,120	4,362	4,229	5,371	4,086
4,232	3,657	4,175	8,770	4,082	3,899	5,508	3,842
4,335	3,733	4,137	8,477	4,177	4,038	5,314	3,898
4,609	4,059	4,240	8,762	4,516	4,381	5,601	4,197
4,781	4,334	4,800	8,770	4,852	4,712	5,982	4,476
4,761	4,447	4,720	8,527	4,889	4,767	5,858	4,560
4,740	4,408	5,094	8,719	4,808	4,653	5,990	4,549
4,812	4,498	4,749	9,149	4,809	4,683	5,792	4,631
4,883	4,412	4,991	9,308	4,814	4,647	6,317	4,574
5,036	4,486	5,170	9,915	4,873	4,697	6,311	4,701

luded). Although this procedure may result in minor discrepancies due to small differences in th
ssification of exploratory wells by the two compiling sources, it seems preferable to maintain Lahee'
inition of exploratory wells consistently throughout this monograph.

real costs of discovering new reserves. On the average, it takes the deepest drilling to produce successes. The deeper a successful wildcat is today, the deeper all future development wells in such fields are likely to have to be in later years. The trend equation for all new field wildcats is:

$$Y' = 4{,}161.4 + 86.48X$$

where Y' is the average depth of new field wildcats in feet
X is time in years ($1947 = 0$)

The standard error of estimate is 237.9 feet. This equation indicates that the average new field wildcat well is increasing in depth at a rate of about 86.5 feet per year. Such an increase can mean a substantial increase in costs as the average depths of new field wildcats increase. For successful new field wildcats, however, the relationship is:

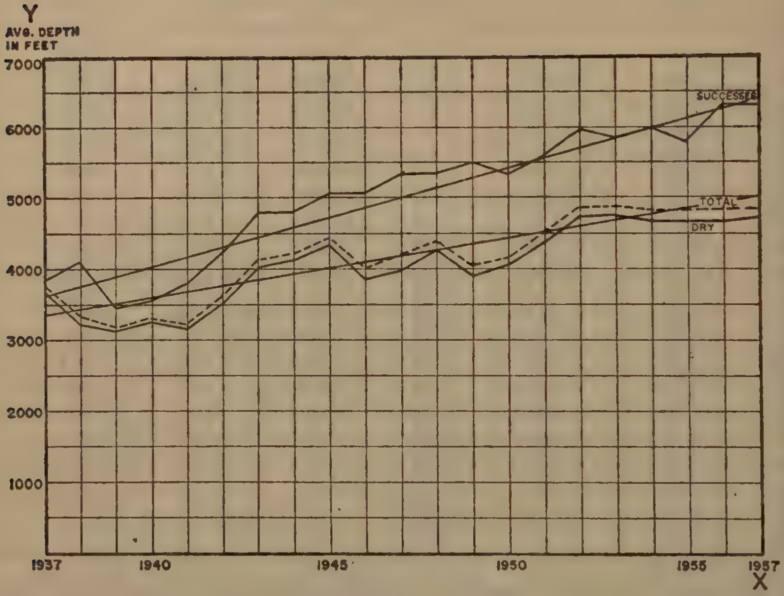

Chart X: New Field Wildcat Wells: Average Depth of Dry Wells, Successful Wells, and Total Wells, 1937-1957.

$$Y' = 5{,}052.4 + 139.3X$$

where Y′ is the average depth of successful new field wildcats in feet
X is time in years (1947 = 0)

The standard error of estimate is 264.4 feet. The yearly increase of 139.3 feet in average depth is very substantial, especially when one considers that the average depth of successful new field wildcats was 6,311 feet in 1957.

Chart XI shows the success rates for the various classes of exploratory wells for the period 1937-57, where such data are available. The most striking fact here is the stability of the success rate of new field wildcats, which seems to fluctuate around a level of 10 per cent to 12 per cent with very little variation from year to year. (As we shall see presently, however, a constant success ratio is consistent with increasing real costs if the average depth per well increases, or if the average size of pool discovered decreases.) New pool wildcats seem to have declined in their success ratio since about 1946, although this was to some extent reversed by the trend from 1953 to 1955. Outposts seem to have followed a more or less horizontal trend since 1943, with some slight evidence of a recent increase in the success rate. Shallower-

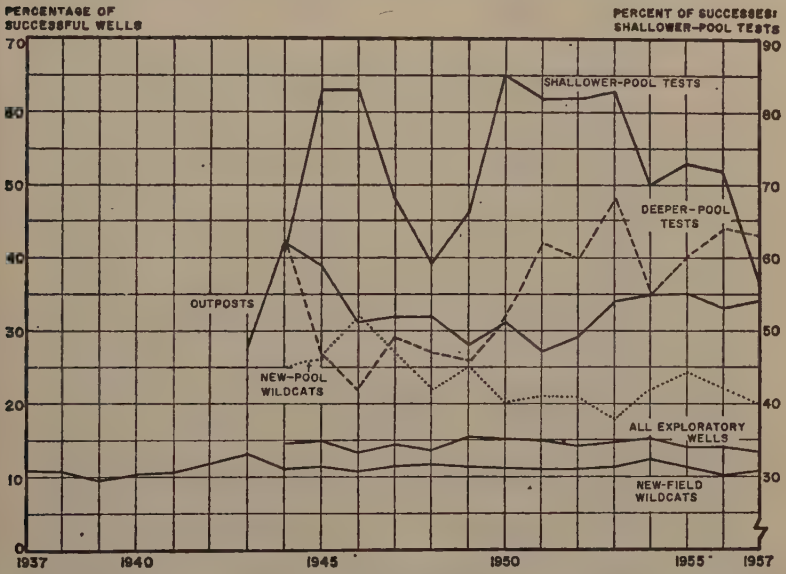

Chart XI: Exploratory Wells: Percentage of Successful Wells, by Class of Well, 1937-1957.

TABLE XI

EXPLORATORY WELLS: PERCENTAGE OF SUCCESSFUL WELLS, BY CLASS OF WELL, 1937–1957

Year	Percentage Successful by Well Classes						Per Cent of Expl. Wells Finding Oil	Successful Wells in Each Category as Per Cent of all Expl. Wells				
	All Expl. Wells	Out-posts	New-Pool Wild-cats	Deeper-Pool Tests	Shal-lower-Pool Tests	New-Field Wild-cats		Out-posts	New-Pool Wild-cats	Deeper-Pool Tests	Shal-lower-Pool Tests	New-Field Wild-cats
1937						11.0						
1938						10.8						
1939						9.4						
1940						10.4						
1941						10.6						
1942						11.7						
1943	17.8	28				13.1						
1944	19.7	42	25	42	61	11.0	14.8					
1945	21.4	39	26	27	83	11.6	15.0	8.4	3.7	3.2	0.6	6.3
1946	19.8	31	32	22	83	10.7	13.2	8.0	4.2	1.8	0.4	5.8
1947	20.3	32	27	29	68	11.3	14.5	7.3	4.7	1.6	0.4	5.8
1948	18.3	32	22	27	59	11.7	13.7	7.0	4.8	1.6	0.4	6.3
1949	20.2	28	25	26	66	11.4	15.5	6.7	4.0	1.4	0.6	5.6
1950	19.5	31	20	32	85	11.2	15.3	7.6	5.2	1.0	1.1	5.7
1951	18.9	27	21	42	82	11.0	15.0	5.8	3.9	1.5	1.3	5.8
1952	18.8	29	21	40	82	11.0	14.3	5.7	4.2	1.4	1.3	5.9
1953	20.1	24	18	48	83	11.2	14.9	5.4	4.5	1.3	0.8	5.8
1954	20.7	35	22	35	70	12.2	15.2	7.0	3.8	1.2	1.1	6.9
1955	20.8	35	24	40	73	11.3	14.1	7.5	4.1	1.2	1.2	6.1
1956	20.1	33	22	44	72	10.0	14.1	7.4	4.7	1.3	0.6	5.4
1957	20.1	34	20	43	56	10.9	13.2	7.4	4.4	1.2	0.5	5.9

Source: F. H. Lahee, in July issue of the *Bulletin of the American Association of Petroleum Geologists.*

pool and deeper-pool tests show such erratic variations that it is difficult to say if any trend is present; since about 1950 the former has decreased markedly, and since about 1949 the latter has increased somewhat. However, there seem to be no general conclusions which we can draw from these changing success patterns, apart from the dependable constancy of the success rate of new field wildcats.

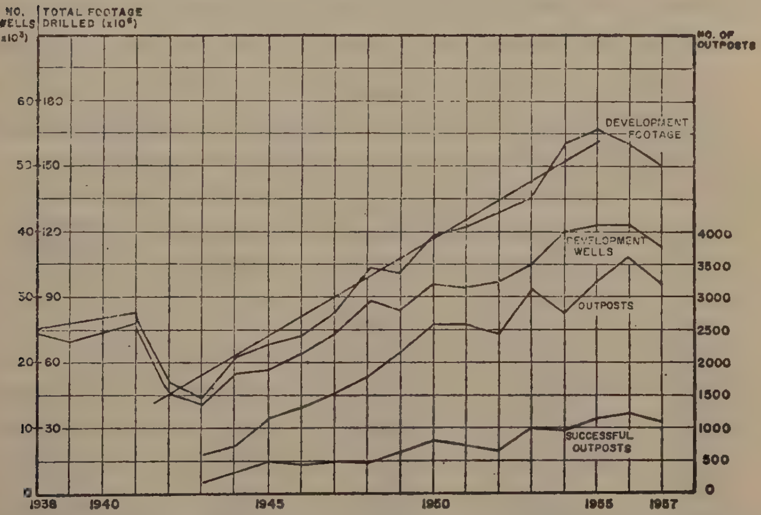

Chart XII: Development Wells: Number and Total Footage, 1938-1957; Outpost Wells: Number and Total Successful Outpost Wells, 1943-1957.

Chart XII presents information on the rate of developmental drilling, both in terms of wells drilled and footage drilled, for the period 1938-57. It also shows the trend in the number of outpost exploratory wells, and the number of successful outposts. These data are presented in conjunction since the outpost well is the closest exploratory well equivalent to the developmental well, in that the developmental well, proper, simply exploits as-yet-undrilled areas of proved oil pools, while the outpost well is drilled in an attempt to make a long lateral extension to reserves in the vicinity of a known pool. Here the situation is roughly similar to that encountered in the investigation of exploratory drilling, except that developmental drilling fell off more markedly during the war than exploratory efforts, which suffered no setback whatsoever with the possible exception of a slight drop from 1941 to

TABLE XII

DEVELOPMENTAL WELLS: NUMBER AND TOTAL FOOTAGE, 1938–1957; OUTPOST WELLS: TOTAL NUMBER, AND NUMBER OF SUCCESSES, 1943–1957

Year	Developmental Wells	Developmental Footage (Thousand Feet)	Number of Outposts	Number of Successful Outposts
1938	24,167	76,246		
1939	23,595	78,804		
1940	25,056	80,326		
1941	26,423	82,315		
1942	14,852	47,451		
1943	13,876	42,600	681	191
1944	18,308	62,001	755	315
1945	19,053	68,456	1,213	480
1946	21,229	71,571	1,357	424
1947	24,118	83,184	1,542	489
1948	29,345	100,963	1,766	490
1949	28,575	101,998	2,152	668
1950	31,733	117,135	2,521	780
1951	31,412	120,954	2,505	682
1952	31,983	127,879	2,429	706
1953	34,745	134,845	3,030	982
1954	39,811	159,405	2,632	923
1955	40,985	167,097	3,204	1,118
1956	40,938	159,921	3,623	1,207
1957	37,399	150,268	3,217	1,084

Sources: Number of development wells and total development footage derived from *World Oil* data on total wells and footage drilled, less the number and footage of service wells, as reported by *World Oil*, and less the number and footage of exploratory wells, as reported by F. H. Lahee in the *Bulletin of the American Association of Petroleum Geologists*. Figures on development wells are therefore residuals. Outpost well data are those reported by F. H. Lahee.

1942. The rate of increase of developmental drilling was less rapid in the postwar period, and as is the case with exploratory wells, the rising trend seems to have ended about 1954-55. It is interesting to note that the number of developmental wells increased considerably in 1954, precisely at the time when exploratory wells were decreasing. It seems plausible to conjecture that the industry decided to substitute more developmental drilling in place of exploratory drilling, in an effort to maintain reserves when the returns to exploratory drilling had been falling off for a number of years. But Table X reveals that this increase in the intensity of developmental drilling was accompanied by diminishing returns in the form of the lowest rate of success and the highest rate of dry holes experienced in development drilling since the war year of 1943. In 1955, exploratory drilling increased once again, but developmental wells scarcely rose above the 1954 level. Total developmental footage fell off after 1955 and this decrease was accompanied by an increase in the success rate. In 1957, both exploratory and developmental drilling declined appreciably.

It is of at least historical interest to compute the trend in total footage that prevailed in developmental drilling before the trend seems to have broken. Here, as in the case of exploratory drilling, our chief interest will be in the rate of increase per year. The trend equation for the period 1944-55 is:

$$Y' = 109{,}624 + 9{,}496.8X$$

where Y' = total footage, in thousands of development feet
X = time in years $(1950 = 0)$

The standard error of estimate is 4,841,400 feet. This trend equation would indicate an increase of 9,496,800 feet per year in developmental drilling. This is in marked contrast to the decrease in total footage from 1955 to 1957, but in 1957, at least, the rate of drilling was not sufficient to maintain reserves, and an increase in the future is more than likely, although not necessarily at the same rate as was experienced in the past. Chart XII also shows that the drilling of outpost wells followed the general pattern of exploratory drilling more closely than it did that of developmental drilling. Outposts increased at a greater rate than developmental wells as a whole, and when the number of developmental wells increased in 1954, the number of outposts decreased, as did the number of exploratory wells generally.

Table X shows that the percentage of developmental wells which have been dry has increased in the postwar period, but apart from the year 1954, the increase has not been very marked. The trend in gas-producing developmental wells is somewhat downward, rather surprising in view of the increasing proportion of natural gas in the total petroleum industry output picture, but it is by no means improbable. The trend in the rate of oil discovery has been gently downward, with a temporary reversal of the trend in 1955. The percentage of developmental wells producing condensate has been fairly steady at a little less than one per cent.

Chart XIII shows the trends in the average depth of developmental wells by their discovery category. The trend in general is unmistakably an increasing one, although the rate of increase is less marked than in the case of exploratory wells. As far as the pattern of relative well depths by categories is concerned, we find much the same picture as was present in the case of exploratory wells. Dry wells are generally the shallowest category, on the whole. Oil-producing wells have generally been the deepest of the major categories, but the average depth of gas wells has been increasing more

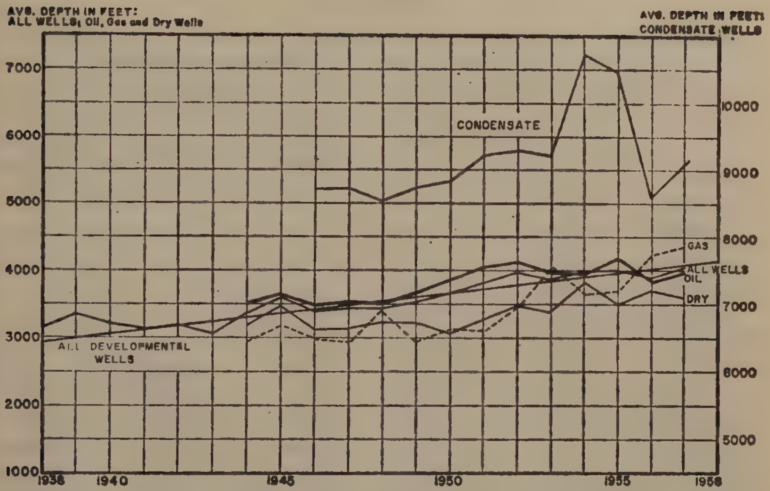

Chart XIII: Development Wells: Average Depths by Discovery Classes, 1938-1957.

rapidly since about 1951, and average gas well depths have been above oil well depths for three of the last five years. Condensate wells are the deepest wells on the average, but they consist of a very small sample of wells, and the average depth of well can therefore vary erratically.

The trend equation for the average depth of a development well since 1937 is as follows:

$$Y' = 3{,}563.4 + 52.61X$$

where Y' = average depth of a development well, in feet
X = time in years ($1948 = 0$)

The standard error of estimate is 120.9 feet. During this period of some 20 years, the average development well increased in depth by some 52.6 feet per year, or only a little more than one-half the rate of increase experienced in the average depth of exploratory wells.

Charts XIV and XV and Table XIV present a convenient

TABLE XIII

DEVELOPMENT WELLS: AVERAGE DEPTHS BY DISCOVERY CLASSES, 1938–1957

Year	Average Depth of Development Wells (Feet)				
	All Wells	Dry Wells	Oil Producers	Gas Wells	Condensate Wells
1938	3,155				
1939	3,340				
1940	3,206				
1941	3,115				
1942	3,195				
1943	3,070				
1944	3,387	3,188	3,500	2,877	
1945	3,593	3,452	3,636	3,171	
1946	3,380	3,105	3,498	2,991	8,702
1947	3,449	3,172	3,547	2,950	8,730
1948	3,441	3,226	3,505	3,436	8,524
1949	3,569	3,225	3,684	2,951	8,736
1950	3,691	3,089	3,861	3,136	8,832
1951	3,850	3,255	4,061	3,106	9,229
1952	3,998	3,494	4,167	3,472	9,302
1953	3,881	3,401	3,972	4,090	9,187
1954	4,004	3,835	3,987	3,633	10,775
1955	4,020	3,510	4,201	3,711	10,489
1956	3,096	3,709	3,867	4,224	8,608
1957	4,018	3,607	3,944	4,380	9,132

Source: *World Oil*, adjusted by means of data on exploratory wells compiled by F. H. Lahee. (See Table XII for details.)

summary of all of the factors mentioned above—increasing well depth, varying success ratios, shrinking average size of oil pools—in terms of ten alternative and supplementary indexes of the real cost of finding oil. Five of these indexes are stated in terms of the returns to drilling activity on a per-well basis, and the other five are stated in terms of returns on a per-foot-drilled basis. Let us look at these measures individually.

Series *a* and *b* measure the trends in barrels of new discoveries of crude oil per exploratory well and per exploratory foot. This is one of the most meaningful direct comparisons

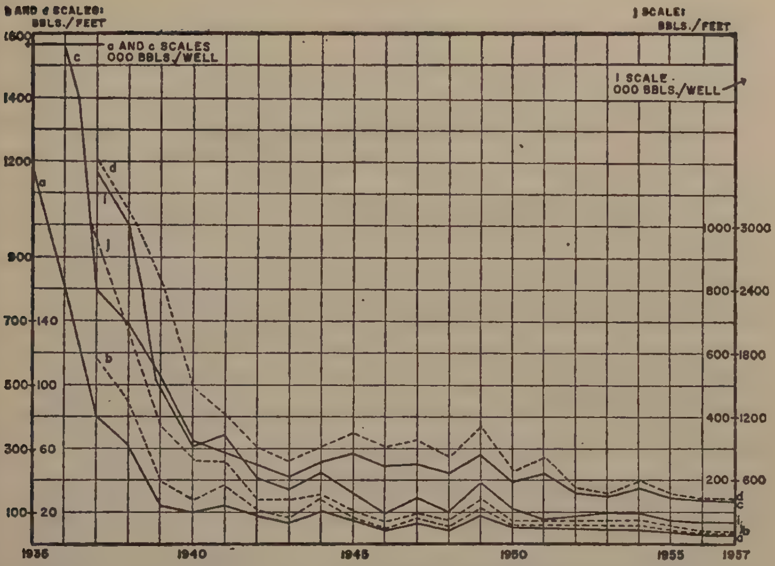

Chart XIV: New Discoveries and Extensions of Crude Oil Reserves per Exploratory Well and per Exploratory Foot, 1935-1957. Line a: New discoveries in thousands of barrels per exploratory well. Line b: New discoveries in barrels per exploratory foot. Line c: New discoveries and extensions in thousands of barrels per exploratory well. Line d: New discoveries and extensions in barrels per exploratory foot. Line i: New discoveries in thousands of barrels per successful oil-producing exploratory well. Line j: New discoveries in barrels per successful oil-producing exploratory foot.

in the whole field of drilling activity. Exploratory outlays are primarily designed to result in new discoveries, so that a very appropriate measure of the success of these outlays would be the amount of oil discovered in barrels per well or per foot. The data in Chart XIV show that both these two series have fallen very far indeed since 1935. The number of barrels per well has fallen from about 1,200,000 in 1935 to about 28,000 by 1957, the decline being virtually unbroken. The decrease was precipitous from 1935 to 1939, and since then the de-

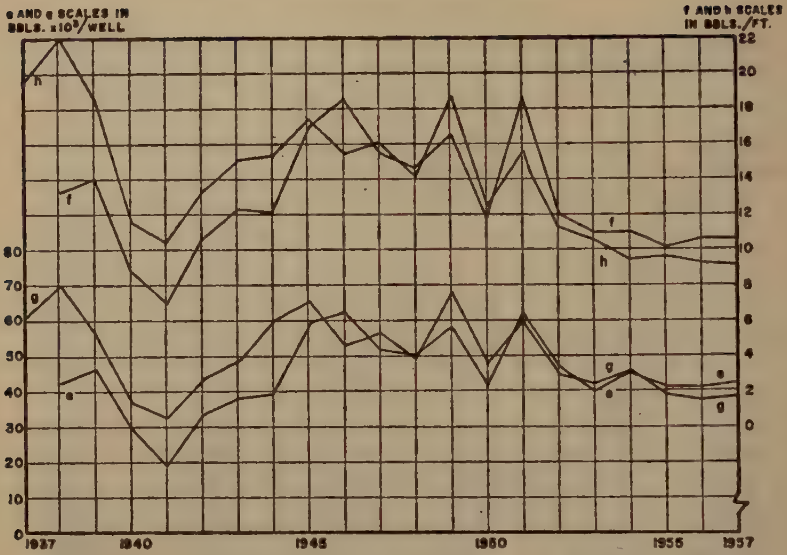

Chart XV: New Discoveries and Extensions of Crude Oil Reserves per Development Well and Per Development Foot, 1937-1957. Line e: Extensions in thousands of barrels per development well. Line f: Extensions in barrels per development foot. Line g: New discoveries and extensions in thousands of barrels per exploratory and development well. Line h: New discoveries and extensions in barrels per exploratory and development foot.

crease has been significant (the rate of discovery in 1957 was only about 25 per cent of that of 1940) but relatively slower, like the declining ranges of a hyperbolic curve. The number of barrels per foot has fallen relatively more rapidly than barrels per well since 1937, since average depth has increased over the period, but unfortunately we cannot extend the footage series back beyond 1937, for lack of data, so that we cannot compare 1935-37 for any of our footage series. From over 120 barrels per foot in 1937, the discoveries per foot have dwindled to an average of less than 10 barrels per foot in 1952-54, and still further to about 6.4 barrels per foot in 1955-57.

TABLE XIV

INDEXES OF SUCCESS OF CRUDE OIL FINDING EFFORTS, PER WELL AND PER FOOT, 1935–1957

Year	New Disc. Per Expl. Well (Thou. bbls.)	New Disc. Per Expl. Foot (Barrels)	New Disc. & Extensions Per Expl. Well (Thou. bbls.)	New Disc. & Extensions Per Expl. Foot (Barrels)	Extensions Per Devel. Well (Thou. (bbls.)	Extensions Per Devel. Foot (Barrels)	New Disc. & Extensions Per Expl. and Devel. Well (Thou. bbls.)	New Disc. & Extensions Per Expl. & Devel. Foot (Barrels)	New Disc. Per Successful Oil-Finding Wildcat Well (Thou. bbls.)	New Disc. Per Successful Oil-Finding Wildcat Foot (Barrels)
1935	1,207		1,550							
1936	829		1,720							
1937	400	120.3	817	246.0			60.0	19.5	3,546	1,033
1938	307	91.4	713	212.4	42.2	13.4	70.4	22.1	2,774	696
1939	126	38.7	537	165.1	46.5	13.9	55.2	18.0	1,504	378
1940	94	27.9	335	99.4	28.1	8.8	36.3	11.4	947	264
1941	131	36.9	300	84.4	19.9	6.4	33.0	10.4	1,031	260
1942	81	21.4	243	64.3	33.6	10.5	43.0	13.1	634	152
1943	70	17.9	215	54.8	37.3	12.1	48.1	14.8	532	136
1944	107	25.3	259	61.5	39.8	11.7	60.9	15.1	721	174
1945	75	18.2	282	68.6	59.9	16.7	64.3	17.3	499	112
1946	42	11.0	243	63.2	61.8	18.3	52.0	14.9	320	71
1947	66	16.9	253	65.0	52.6	15.3	55.5	15.7	454	104
1948	49	12.1	229	59.1	49.1	14.3	49.1	13.7	361	81
1949	98	25.6	285	74.3	59.3	16.6	68.5	18.9	633	150
1950	55	14.1	184	47.3	42.0	11.4	45.2	12.1	357	82
1951	33	7.9	224	53.5	71.6	18.6	61.1	15.5	221	48
1952	40	8.9	161	36.1	47.2	11.8	45.2	10.9	279	58
1953	44	9.8	153	33.5	41.4	10.7	42.2	10.4	299	63
1954	43	9.8	171	39.1	43.9	11.0	44.1	9.3	295	62
1955	32	6.9	146	31.4	41.4	10.2	38.8	9.6	213	46
1956	29	6.3	134	29.3	41.6	10.6	37.8	9.3	205	42
1957	28	6.0	137	29.1	42.6	10.6	38.6	9.2	214	42

Sources: Wells, See Tables IV and X. Reserves, 1935–46, derived from *World Petroleum*, July 1954, pp. 44, 60, 62; 1947–57, American Petroleum Institute.

TABLE XV

MEASURES OF THE COSTS OF FINDING, DEVELOPING, AND PRODUCING CRUDE OIL AND ALL FLUID HYDROCARBONS: 1948, 1951, 1953, 1955

	Finding Cost Per Unit of New Disc.	Dev. Cost Per Unit of Extensions	Dev. Cost Per Unit of Extensions & Revisions	Prod. Cost Per Unit of Production	Find. Cost Per Unit of New Disc. & Revisions	Finding & Dev. Cost Per Unit of Total Disc.	Total Cost Per Unit of Total Disc.
Ia. Costs Expressed in Current Dollars Per Barrel of Crude Oil Alone							
Year	(1)	(2)	(3)	(4)	(5)	(6)	(7)
1948	$2.664	$1.061	$ .450	$ .656	$ .459	$ .681	$1.027
1951	4.116	.865	.483	.728	.739	.804	1.169
1953	3.302	1.625	.865	.798	1.053	1.030	1.863
1955	4.754	1.684	1.194	.835	1.934	1.704	2.404
IIa. Costs Expressed in Current Dollars Per Barrel of Crude Oil Equivalent (All Fluid Hydrocarbons Converted into Crude Oil Equivalent in B.T.U. Content)							
Year							
1948	$ .861	—[a]	$ .290	$ .398	—[a]	$ .377	$ .569
1951	1.559	—[a]	.274	.407	—[a]	.436	.634
1953	.978	—[a]	.395	.426	—[a]	.537	.775
1955	1.414	—[a]	.488	.438	—[a]	.687	.957
Ib. Costs Expressed in 1947–49 Dollars Per Barrel of Crude Oil Alone[b]							
Year							
1948	$2.677	$1.066	$ .452	$ .659	$ .461	$ .684	$1.032
1951	3.582	.753	.420	.634	.643	.700	1.017
1953	3.000	1.476	.786	.725	.956	.939	1.693
1955	4.314	1.528	1.083	.758	1.755	1.549	2.185
IIb. Costs Expressed in 1947–49 Dollars Per Barrel of Crude Oil Equivalent (All Fluid Hydrocarbons Converted into Crude Oil Equivalent in B.T.U. Content)[b]							
Year							
1948	$ .865	—[a]	$ .291	$ .400	—[a]	$ .379	$ .572
1951	1.357	—[a]	.238	.354	—[a]	.388	.552
1953	.888	—[a]	.359	.387	—[a]	.488	.705
1955	1.283	—[a]	.443	.397	—[a]	.625	.870

[a] Separate figures for natural gas extensions and revisions are not available.

[b] Adjusted by Index of Wholesale Prices, 1947–49 = 100.

Sources: Reserves, American Petroleum Institute and American Gas Association; cost data, C. C. Anderson, "Petroleum and Natural Gas in the United States—Relation of Economic and Technologic Trends," Canadian Sectional Meeting, World Power Conference, September 1958, p. 9; wholesale price index, U. S. Department of Commerce.

Series *c* and *d* measure the trends in barrels of both new discoveries and extensions of crude oil, per exploratory well and per exploratory foot. These measures are devised to reflect the fact that exploratory wells (specifically outposts) sometimes increase reserves through discovering extensions to proved reserves, and not simply through the avenue of new discoveries alone. Also, including extensions will tend to correct for the fact that initial-year estimates of new discoveries are always highly conservative. In both cases, the decline is of the same order of magnitude as was observed in the case of series *a* and *b*. Discoveries and extensions per exploratory well stood at about 1,550,000 barrels in 1935, but had fallen to 137,000 in 1957. Discoveries and extensions per exploratory foot were 246 barrels in 1937, but only 29 in 1957. Here, too, we note that the series based on footage declines somewhat more rapidly than the series based on total wells, indicating the effects of the greater average depth of well.

Series *i* and *j* on the same chart show two other possible ways of measuring the success of exploration efforts in real terms. Here the ratio refers to the number of barrels of crude oil discovered per successful oil-producing exploratory well, or per successful oil-producing exploratory foot. The decline pattern is still the same as before. If we attribute all the new discoveries of crude oil to the successful exploratory wells alone, we find that the average discovery per well was 3,546,000 barrels in 1937, but by 1940 it had dropped to 947,000 barrels per well, and by 1957 it had fallen 77 per cent below the 1940 level to 214,000 barrels per well. For the alternative measure, new discoveries of crude oil per successful exploratory foot, the decline is about 25 per cent greater, owing to the increase in the average depth of the exploratory well over this period. Discoveries per successful exploratory foot were 1,033 barrels in 1937, but had fallen to 264 barrels per foot in 1940, and had fallen 83 per cent below the 1940 level by 1957, when only 42 barrels of crude oil were found per successful exploratory foot.

Chart XV presents information which takes into account not only the volume of reserves acquired through initial-year estimations of new discoveries, but also includes those reserves added by extensions to reserves discovered in prior years. Series *e* and *f* attempt to measure the trend in the real cost of proving reserves through extensions, on the assumption that only developmental wells contribute toward these extensions. This is an oversimplification because, as mentioned before, outpost exploratory wells can also contribute to extensions of the reserve capacities of known oil pools, but the ratio in which these two classes of wells contribute to extensions is not known. It was therefore considered instructive to investigate the trends in extensions per developmental well and per developmental foot primarily for the sake of the trend, keeping in mind the restrictive assumption employed in making the calculations.

Series *e* shows that extensions per development well have fluctuated irregularly, with a level of 42,200 barrels per well in 1938 and an almost identical figure of 42,600 barrels per well in 1957. During the interim, a minimum of 19,900 barrels per well was reached in 1941, followed by a steady increase up until 1946, when 61,800 barrels were discovered per well. Since that time the trend has been mildly downward, but was broken by two years of extremely high extensions, 1949 and 1951. Series *f* shows essentially the same pattern, with the decline again being relatively greater on a per-foot basis because of the increasing average depth of developmental wells, although since their depth has not been increasing as rapidly as that of exploratory wells, the contrast between the two series is not as marked as it is in the case of exploratory wells. Extensions per developmental foot were 13.4 barrels in 1938, and had fallen to 10.6 by 1957. The trend in between followed that of series *e*, with a trough in 1941, and peaks of approximately equal height in 1946, 1949, and 1951. The decline since 1951 is notable, and practically unbroken. The interpretation of this series must remain incomplete until the relationship is clarified between new discoveries in one year and extensions to these discoveries in the following years. No information is available on which to base definite conclusions about such a relationship; it seems most plausible to suppose that there is perhaps a two or three year lag between new discoveries and the appearance of major extensions to these new discoveries, but sufficiently detailed statistics are not available on the relationship of the new discoveries of one year to subsequent year extensions (and revisions) of these discoveries.

The final pair of series, series g and *h* of Chart XV, recognizes the fact that both exploratory and developmental wells can contribute to both new discoveries and extensions, and therefore these series show the discoveries of crude oil through both new discoveries and extensions, per exploratory and developmental well, and per exploratory and developmental foot. Series g has a generally declining trend which resembles that of series *e*, both series being affected strongly by the war years with their relative curtailment of developmental drilling. The trend of series g is, however, more unequivocally downward since about 1945. New discoveries and extensions per exploratory and developmental well were at 70,400 barrels in 1938 and had fallen to 38,600 barrels by

1957. The peak years in this series were 1945, 1949, and 1951, the years of large extensions. Since 1949, the decline has been consistent although it levelled out a bit in 1955-57.

Series *h* shows that new discoveries and extensions per exploratory and developmental foot have declined more rapidly than series *g* on a per-well basis. Series *h* has also fallen more rapidly than its development-well counterpart, series *f*. From a peak of 22.1 barrels per foot in 1938, series *h* has fallen to 9.2 barrels per foot by 1957. Series *f* and *h* show the same general configuration, but here it should be noted that the decline since 1945 has been more pronounced in these composite series than it has been in any of the others. The successive peaks in 1945-46, 1949, and 1951 have been at successively lower levels of average discoveries per foot. It might be useful to compare series *h* with the data in Chart VII, where total discoveries from extensions, revisions, and new discoveries, are divided by total footage drilled in all drilling categories to establish a measure of the success of gross drilling per foot. Here also we have an unmistakable downward trend from the late 1930's through 1957, but our peak years are 1942, 1946, 1948, and 1951. The chief difference between the data in Chart VII and the data of series *h* of Chart XV is that the former includes the element of revisions of prior year reserve estimates, while we have considered it preferable to omit these revisions in the latter calculation. It seems preferable to omit it because the category of revisions seems to be that component of total additions to cumulative discoveries which fluctuates most erratically from year to year, and since it arises out of underestimations of new discoveries in prior years, it is not logical to allocate it to either the current year exploratory wells or current developmental wells. (The case is much better for assuming that it is meaningful to compare developmental drilling and current extensions, although it is by no means beyond question even in this instance.) The relationship between *current* exploratory and developmental drilling, and current revisions of prior year estimates, seems however to be entirely too tenuous and indirect to hazard any sort of assumption as to the relationship without a careful study of the problem, and such a study is made impossible by lack of relevant data. We might conjecture that some relationship could be verified, perhaps along these lines: take a moving average (three, four, five or more years) of revisions in order to remove the extremes of the element of random fluctuations, and then lag this moving average behind new discoveries by a certain number of years, experimenting to see which lag would give the best fit. It might be necessary to introduce several lagged variables to "explain" the volume of revisions: new discoveries, and probably extensions as well, and perhaps even the variable of total cumulative discoveries of crude oil to date, since the potential for current revisions depends not only on drilling in the recent past, but also upon all previous drilling. (It might be better to substitute total current proved reserves for total cumulative discoveries, but this would have to be decided in the light of the statistics.)

The statistical series given in Charts XIV and XV, and in Table XIV, must therefore be interpreted with the reservation that all of them somewhat understate the total success of current and past historical outlays on exploration and development, since they omit revisions of prior year estimates in order to minimize the extent of inter-year distortion by having the results of the outlays of prior years affect too greatly the results of current year outlay computations. On the whole, then, total returns to exploration and development since 1938 have been somewhat greater than any of the series *a* through *j* would indicate, but these series have been computed for the sake of illustrating the nature of the *trends* in drilling success, not the absolute level of total discoveries in any year. Including this information through the inclusion of revisions would only obscure the trend relationships; if this information is desired, it may be obtained from Chart VII.

At this point the survey of the trends in the *real* cost of finding oil is substantially completed. Before concluding with a survey of the relatively scantly published information on the total money costs of finding reserves, it might be best to draw what conclusions we can from the evidence on real costs presented above.

The data all seem to support the hypothesis that the phenomenon of diminishing returns to exploratory drilling is being experienced with increasing severity from year to year, and has been operating more severely ever since about 1937-1939, the period of the lowest per-well and per-foot real costs of discovery. Diminishing returns have, therefore, been operating for several years prior to the postwar period, from which the current era of increasing costs is usually dated. The data in Charts XIV and XV seem to bear out these conclusions, and Charts I-IV are intended to place the problem in a more adequate historical perspective. Whether or not the basic cause of the severity of diminishing returns and increasing real costs since 1937-39 is the failure of exploration technology to open up new horizons of exploration possibilities through the inauguration of a fourth "era" of discovery techniques, is a matter for conjecture; it may or may not be possible to devise further *basic* improvements in exploration technology within the limitations of oil-finding budgets;

nevertheless, it is quite plausible to interpret the facts in the light of the hypothesis that it is still possible. Of all the statistical data herein assembled, the most significant for the future are perhaps (1) the trend equation in Chart IV referring to the future productivity of exploratory wells, (2) the equation for the increasing average depth of successful new-field wildcat wells in Chart X, and (3) the real cost indexes of Charts XIV and XV. All of these series may give rise to some pessimism regarding the future; but these series are necessary ingredients in any realistic appraisal of the oil-finding cost situation, and the facts must be regarded as posing a genuine challenge to the industry. It is true that the average level of discoveries is increased very significantly if natural gas liquids and natural gas are included in the discovery base, but Chart VII shows that the rate of decrease in the success rate, thus defined to include all products, is at least as rapid since 1947 as is the decline in crude oil discoveries alone.

Turning now to the final evidence to be presented in this section, a survey of the available data on money costs involved in the finding, development, and production of oil and gas, we are faced with a rather embarrassing lack of acceptable data. What we need are dollar outlays for these categories, but the only reasonably consecutive and comparable estimates that we have are for the years 1948, 1951, 1953, and 1955; and there is no satisfactory way to estimate the statistical validity of even this series. Table XV presents the total cost estimates compiled by C. C. Anderson[38] (briefly discussed in Section I) broken down into the separate components of finding, development, and production costs. The various estimates have been divided by the number of barrels of reserves which may be thought of as attributable to the relevant outlays under a variety of assumptions. Table XV presents the data both in terms of current (unadjusted) dollars, and in terms of current dollars adjusted to a constant dollar basis (1947-49 = 100) by the use of the index of wholesale prices.

In the evaluation of these figures it must be kept in mind that Anderson's cost data refer to current cash expenditures, rather than to costs in the economic sense. Seven different measures have been given in Table XV in an attempt to show rough approximations of the actual trends in the cost of petroleum exploration, development, and production. Each of these seven unit cost measures (or unit expenditure measures) merits some individual comment. In the discussion below, each measure will be taken up separately, using the current dollar figures of Table XV as a basis for discussion.

Finding cost per unit of new discoveries is the ratio of the gross total of industry expenditures for exploration activity to the total number of barrels of crude oil (or crude oil equivalent of all fluid hydrocarbons) added to total cumulative discoveries as the result of discoveries of new fields and new pools in old fields. As such, it is a measure of the money cost of "proving" a barrel of new discoveries in the ground, and does not include any costs expended for development or eventual production of those newly proved reserves. The figures in this series can only be used to demonstrate a general trend, rather than the actual level of "proving" costs. The figures are in some unknown degree biased upward because initial estimates of new discoveries are always conservatively estimated. For crude oil alone, the current dollar trend is definitely upward. Costs rose from $2.664 per barrel in 1948 to $4.116 in 1951, then fell to $3.302 in 1953 but rose to $4.754 in 1955. For total fluid hydrocarbons, the upward trend is less accentuated. Costs in 1955 were below those of

1951, because of larger discoveries of natural gas in 1955.

Development cost per unit of extensions is the ratio of the total of industry expenditures on development activity to the total number of barrels of crude oil added to total cumulative discoveries as extensions to prior estimates of proved reserves. Most extensions result from the drilling of successful development wells. Hence, at least as a first approximation, development cost per unit of extensions is a measure of the cost of adding a barrel to proved reserves through developmental extensions to known fields and pools. It is only an approximation because of the difficulty of estimating accurately the volume of extensions made by a development well. For crude oil alone, the current dollar trend is generally upward, although the increase in unit development cost has not been as pronounced as the increase in unit finding cost. Costs rose from $1.061 per barrel in 1948 to $1.684 in 1955, after having fallen in 1951. (This cost trend can not be computed for total fluid hydrocarbons since data are not available separately for extensions and revisions to natural gas reserves.)

Development cost per unit of extensions and revisions is the ratio of total industry expenditures for development activity to the total number of barrels of crude oil, or of equivalent fluid hydrocarbons, added to total cumulative discoveries as extensions to, and as revisions of, prior estimates of proved reserves in known fields and pools. As was mentioned above, most extensions result from the drilling of development wells, but revisions also depend partly upon past or current exploratory drilling. No information seems to be available on the relative roles played by exploratory and development drilling in arriving at annual estimates of revisions. To ignore revisions entirely would be to overstate the unit cost of "proving" reserves. To credit them to current exploratory drilling would be largely erroneous, since they are revisions of prior estimates and should rather be credited to prior exploratory drilling efforts, if they are to be related to exploratory drilling at all. In the absence of relevant data, there is no reasonable way of crediting revisions to prior exploratory drilling. By default, one must therefore credit them to current development drilling, or ignore them altogether. Both expedients have been employed in Table XV. The third column of cost data attributes both extensions and revisions to current development outlays. For crude oil alone, the current dollar trend is markedly upward, a steady increase from $.450 to $1.194 per barrel having taken place. For equivalent fluid hydrocarbons, the trend is also unbroken in an upward direction (from $.290 to $.488 per barrel) although the rate of increase is not as great.

Production cost per unit of production is simply the ratio of the total of industry expenditures on current production to the total number of barrels of crude oil or equivalent fluid hydrocarbons actually produced during the current year. The comparison is straightforward, and the resulting cost figure is meaningful both as a measure of the absolute level of costs and of year-to-year trends in costs. Production costs have shown an unbroken increase for these four years, although the increase is more moderate than is the case for finding or development costs. For crude oil alone, current dollar production cost per barrel increased from $.656 to $.835; for equivalent fluid hydrocarbons, the increase was only from $.398 to $.438.

Finding cost per unit of new discoveries and revisions has been computed simply to supplement the other cost comparisons. As was mentioned immediately above, it is more logical to match current revisions with the finding costs of the relevant prior years. Nevertheless, in column five, current revisions as well as current new discoveries are attributed to current finding efforts. In this indirect measure of cost trends, the absolute level of the individual figures is not of particular significance; the trend of the figures may be of significance, depending upon the relationship of revisions to prior new discoveries. (If the relationship of current new discoveries to future revisions is reasonably stable, the trend may be of real significance; if not, it is largely meaningless.) For crude oil alone, the current dollar trend displays the most pronounced increase of all the series shown in Table XV. The 1948 level was $.459 per barrel, but by 1955 the cost had increased to $1.934 per barrel, a 321 per cent increase above the 1948 level. Primarily, this means that for crude oil, the ratio of revisions to current new discoveries has been declining. The sharpness of the rising trend would provoke one to speculation. It may be the case that the post-1940 decrease in the average size of newly discovered fields has been accompanied, in later years, by a more than proportionately smaller level of subsequent revisions. If this were the case, new discoveries might actually increase in total volume if enough exploratory wells were drilled and a sufficiently large number of small fields and pools were discovered. Nevertheless, with a relatively much smaller potential for revisions, the volume of revisions would decline. Such speculation is perhaps unwarranted, owing not only to the lack of specifically relevant supporting data, but also to the fact that revisions fluctuate greatly from year to year. Unfortunately this series cannot be computed for equivalent fluid hydrocarbons because of the lack of separation of natural gas extensions and revisions. It seems likely, however, that the rate of increase for total equivalent fluid hydrocarbons would be smaller than that displayed for crude oil alone.

Finding and development cost per unit of total discoveries is the ratio of the gross total of industry expenditures for exploration and development activity to the total number of barrels of crude oil or equivalent fluid hydrocarbons added to total cumulative discoveries through new discoveries, extentions, and revisions. As a gross estimate of the cost per barrel of "proving" reserves, it has some limited value in terms of the absolute level of costs, but is of more value as an indication of longer-run cost trends. For crude oil alone, the current dollar trend is sharply upward, increasing from \$.681 per barrel in 1948 to \$1.704 per barrel in 1955. For equivalent fluid hydrocarbons, the rate of increase is only about two-thirds as great, from \$.377 in 1948 to \$.687 in 1955.

Total cost per unit of total discoveries is the ratio of the gross total of industry expenditures on exploration, development, and production activity to the total number of barrels of crude oil or equivalent fluid hydrocarbons added to total cumulative discoveries through new discoveries, extensions, and revisions. This comparison has been included to complete the survey of plausible measures of cost, although for most purposes the measure discussed immediately above is preferable. Production costs would seem to bear relatively little relationship to exploration and development activities. As is apparent from Table XV, the addition of production costs increases the level of unit costs, but has only a slight effect on the trend. Since production costs have increased relatively less rapidly than finding and development costs, the effect on the trend is to diminish its rate of increase slightly.

The lower portion of Table XV presents the same data in terms of constant 1947-49 dollars. The simple adjustment of current dollar values by the index of wholesale prices yields only a very approximate correction for the actual net effect of changing price levels on petroleum industry operations. Nevertheless, it is a useful supplement to the unadjusted current dollar figures. The apparently large increase in costs between 1948 and 1951 was to some extent due to higher prices. If we adjust these data by the wholesale price index as shown in Table XV, we find that "real" costs increased from $.572 in 1951 to $.870 in 1955, for total cost per unit of total discoveries. However, there is evidence that the wholesale price index does not accurately measure changes in prices affecting the industry.[39] Specifically, the wholesale price index actually declined during this period while the prices of steel, labor, and other major oil industry cost elements were increasing. Therefore, the increase in the "real" cost of finding, developing, and producing oil from 1951 to 1955 was actually somewhat less than the adjusted dollar figures would suggest. However, the price adjusted data in Table XV show that a part of the increase in industry costs between 1948 and 1955 was due to an increase in the general price level. The remainder of the increase must reflect an increase in the "real" cost of the operations involved. To take only one instance by way of example, the finding and development cost per unit of total discoveries of crude oil increased by 150 per cent between 1948 and 1955 on the basis of current dollars, and after being adjusted to the constant dollar basis, the cost increase was still 126 per cent. Since the same price level adjustments were made for all series, similar relationships will prevail for all other comparisons between pairs of years.

FOOTNOTES AND REFERENCES

[1] See, for example, *World Petroleum Statistical Yearbook,* No. 1, 1954-1955; *World Petroleum Report,* 1956; *World Petroleum,* March 1954, pp. 66-68, and July 1954, pp. 42-45, 60, 62.

[2] See especially *World Petroleum,* July 1954, p. 43.

[3] F. H. Lahee, "Exploratory Drilling in 1944," *Bulletin of the American Association of Petroleum Geologists,* Vol. 29, No. 6, June 1945, pp. 631-634.

[4] P. R. Schultz, "Oil Discovery Trends," *Bulletin of the American Association of Petroleum Geologists,* July 1953, pp. 1572-1585.

[5] Schultz does not claim any originality for this measure, remarking that it is one which "industry economists often use." (*Ibid.,* p. 1578.) Since it is almost unknown in the published literature on the subject, this seems to amount to a reflection on the status of communication within the industry, and one which might easily be remedied.

[6] He admits, however, that "The theory behind this substitution is somewhat devious," *Ibid.,* p. 1578.

[7] *Ibid.,* pp. 1578-1579.

[8] *Oil and Gas Journal,* Volume 54, No. 39, Jan. 30, 1956, p. 179.

[9] *Ibid.,* p. 1579.

[10] *Ibid.,* pp. 1582-1583.

[11] *Ibid.,* pp. 1583-1584.

[12] Warren Davis, "A Study of the Future Productive Capacity and Probable Reserves of the United States," *The Oil and Gas Journal,* February 24, 1958, pp. 105-119.

[13] *Ibid.,* p. 106.

[14] *Ibid.*

[15] For details, see reference in footnote 25.

[16] Douglas Ragland, "Well Costs Flatten Out at 1950 Levels," *Oil and Gas Journal,* Nov. 19, 1956, p. 111.

[17] This apparent independence of the drilling rate with regard to any profitability considerations is, beyond doubt, primarily a statistical artifact. It would be more reasonable to assume that, during the period studied, profitability varied in approximately the same manner as total revenue or Gross National Product, or both; but there is no assurance that a basic change in the structure of the determinants of the profitability of drilling may not occur, which would make the neglect of the profitability variable wholly unacceptable.

[18] Davis, *op. cit.,* p. 108. The numerical values in the quotation are the 1956 co-ordinates for price and drilling returns.

[19] *Ibid.,* p. 111.

[20] "This decline in drilling is a critical fact and all of the calcula-

tions made and the conclusions drawn are based on this fact." *Ibid.*, p. 106.

[21] National Petroleum Council Committee on Productive Capacity. Report, dated October 3, 1957.

[22] R. E. Megill, "The Cost of Finding Oil in Oklahoma and Kansas," paper presented before the Tulsa Geological Society, April 25, 1958.

[23] *Ibid.*, pp. 1-2.

[24] R. E. Megill, "Crude Oil Replacement Costs in the Illinois-Michigan Basin Areas," paper presented before the Spring Meeting of the Eastern District of the American Petroleum Institute, Division of Production, Columbus, Ohio, May 7-9, 1958.

[25] This study represents the second survey conducted by the three trade associations to determine the cost of drilling and expenditures for exploration, development, and production in selected years. The first survey covered the years 1944, 1948, and 1953. The cost findings were reported in an information release dated December, 1955. The expenditure estimates were reported in an information release dated April 12, 1956. The second survey covered the years 1955 and 1956. The cost findings were reported in an information release dated June 3, 1959. The expenditure estimates have not been released at the time of this writing.

[26] C. C. Anderson, "Petroleum and Natural Gas in the United States —Relation of Economic and Technologic Trends," Canadian Sectional Meeting, World Power Conference, September 1958.

[27] Strictly speaking, the company does not tie up $600,000 for a period of four years. While $600,000 is invested in 1958, the production and sale of oil, which commences in 1959 and continues through 1962, returns the $600,000 as a cash flow to the company over the four-year period. Where its own funds are used, the returning cash flow can be invested elsewhere. If the company borrows externally, it can amortize the loan out of the revenues from production and reduce its interest expense below the figure assumed in the text. It is felt that the present treatment is justified by its simplicity since no important conclusions are affected by the approximation.

[28] F. H. Lahee, *op. cit.*, p. 632.

[29] J. R. Dodge, H. C. Pyle, and E. G. Trostel, "Estimations by Volumetric Method of Recoverable Oil and Gas from Sand," *Bulletin of the American Association of Petroleum Geologists,* July 1941, pp. 1302-1326.

[30] For example, such estimates may be made by multiplying the first day's production by factors ranging from 240 for wells producing over 600 barrels the first day, to 644 for wells producing less than 100 barrels the first day. See S. F. Shaw, "Review of Ultimate Recovery Factors and Methods of Estimation," *Oil Weekly,* July 13, 1942, p. 24.

[31] See especially the Report of the Cost Study Committee of the Independent Petroleum Association of America, dated April 29, 1957, p. 15.

[32] One B.T.U. is the amount of heat required to raise one pound of water one degree Fahrenheit in temperature. The usual conversion factor is 138,000 B.T.U.'s per gallon for a weighted average of United States crude oils, and 1,050 B.T.U.'s per thousand cubic feet of natural gas, at 60°F. and a pressure of 980 mm. Hg for a weighted average of United States natural gas. Hence one million cubic feet of gas (S.T.P.) is equal to 0.185338 barrels of crude oil by volume. See United States Bureau of Mines official conversion factors, adopted January 3, 1950.

[33] American Petroleum Institute, Independent Petroleum Association of America, and Mid-Continent Oil and Gas Association, "Joint Association Survey Report on Expenditures for Drilling and Equipping Wells in 1953," Information release from American Petroleum Institute, dated December, 1955.

[34] P. R. Schultz, *op. cit.*, p. 1578.

[35] W. A. VerWeibe, *How Oil Is Found*, Edwards, Lansing, Michigan, 1951, p. 235.

[36] American Petroleum Institute, Independent Petroleum Association of America, and Mid-Continent Oil and Gas Association, *op. cit.*, p. 1.

[37] P. R. Schultz, *op. cit.*, p. 1580.

[38] C. C. Anderson, *op. cit.*, p. 9.

[39] The Cost Study Committee of the Independent Petroleum Association of America is currently engaged in constructing an index of industry prices. See the committee report for May, 1959.